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TITLE: DESIGN REPORT ON A DIRECT LIFT CONTROL FLAP FOR THE 367-80 AIRPLANE

MODEL 367-80

ISSUE NO. _____ TO: _____ _____ (DATE)

NASA - BOEING CONTRACT NAS2-4200 PHASE I

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REFERENCES

1. L.B. Gratzer and T. J. O'Donnell, "Development of a BLC High-Lift System for High Speed Airplanes", Journal of Aircraft, Vol. 2, No. 6, November - December 1965, pp. 477-484.

1.0 INTRODUCTION

The purpose of this report is to describe the results of the preliminary design study of a Direct Lift Control flap system for the Boeing 367-80 airplane. This work was done in April - July, 1967, under Contract NAS2-4200. The primary goal of this study was to evolve a design which provides performance meeting the design objectives of NASA ARC Specification A-12848, Paragraph 8.2. Additional design considerations are safety, flexibility of operating mode and relative simplicity in detail to minimize costs. Some of the approaches taken are therefore not representative of a system which would be designed for production. In particular, it was decided at the outset that only qualified flight control actuators would be used to prevent any requirement for actuator development.

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2.0 GENERAL DESCRIPTION

The 367-80 airplane is a 4 turbofan swept wing transport airplane (prototype of C-135 and 707 series) which has been extensively modified for use as a low speed flight research vehicle. A two view drawing of the basic airplane configuration is given in Figure 1.

2.1 Flap Modifications

The basic flap is a plain flap with a blowing slot at the flap hinge line of the wing upper surface for boundary layer control. A detailed description of the basic flap system is given in Reference 1. The modification for Direct Lift Control involves the replacement of the aft approximately 40% of the basic flap chord by a slotted auxiliary flap which is operated by hydraulic actuators to achieve the required high deflection rates for the DLC function. A typical section of the modified flap is shown in Figure 2.

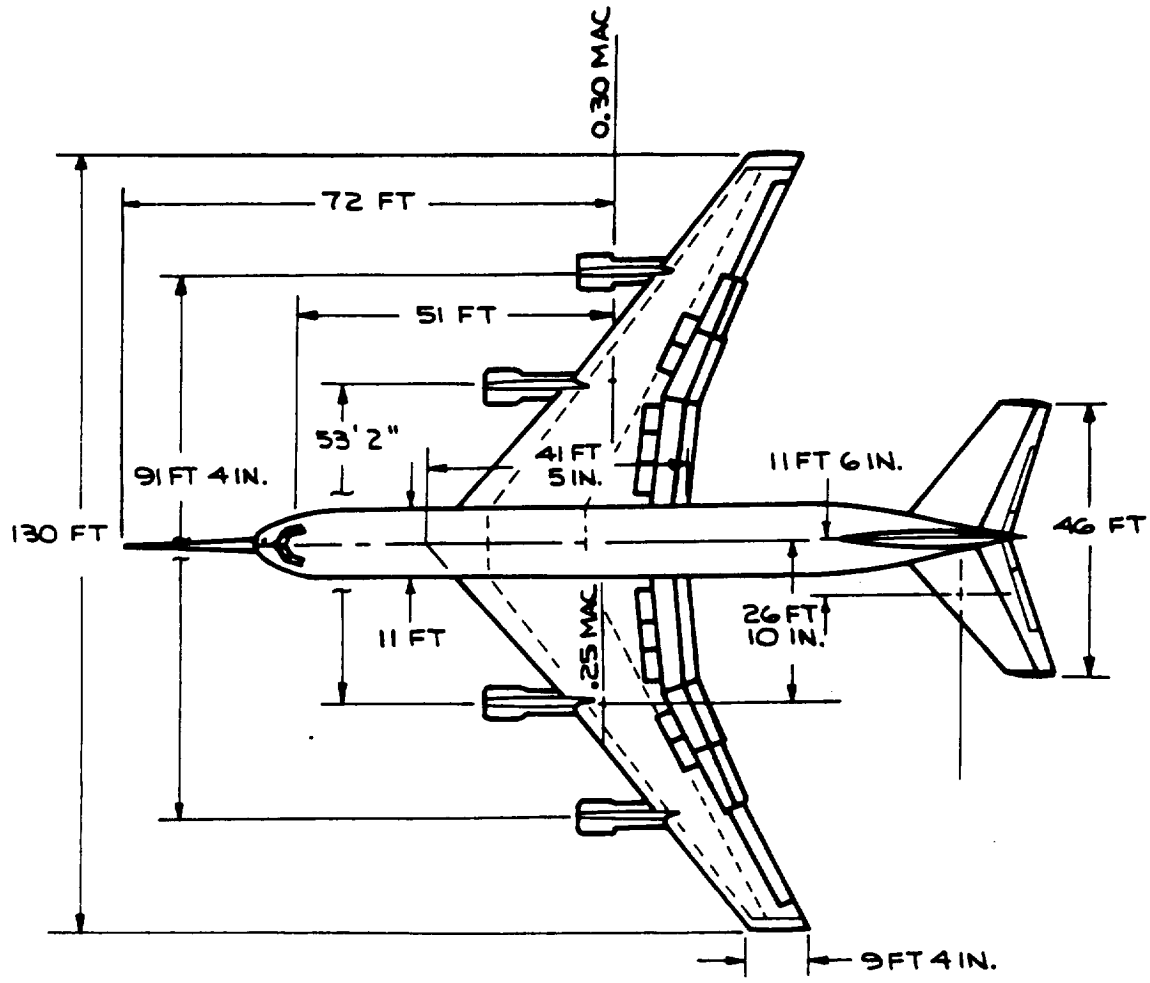
The hinge brackets and actuators for the auxiliary flaps are mounted externally on the flap lower surface for simplicity of design and accessibility. The resulting aerodynamic drag increment is estimated to be small relative to the total airplane drag in landing configuration.

2.2 Auxiliary Flap Actuation and Control

The use of the auxiliary flap as a direct lift control device

makes it a primary control surface with essentially the same requirements for actuation rate and reliability as the conventional control surfaces. The philosophy adopted as a result of these considerations was that the system design should prevent symmetric or anti-symmetric hard-over deflections of the auxiliary flaps as a result of single electrical or hydraulic failures. Actuation is by dual tandem hydraulic power control units (PCU's) which are essentially the same as those used in the elevator control system. The auxiliary flap deflection signals which are generated in the simulation computer and interface are inputs to the PCU electro-hydraulic transfer valves. The mechanical input linkage of the PCU's is grounded to the main flap structure through a spring cartridge. In the event of an electrical disconnect, the auxiliary flaps return to the neutral position determined by the mechanical input.

The auxiliary flap deflection command signals are monitored and logic circuitry is provided to cause a simulation disconnect in case of faults in this or other simulation signals.



WING		
Area	2821.36	ft^2
Aspect Ratio	6.0	
Sweep (0.25c)	35	deg
Incidence	2.0	deg
Dihedral	7.0	deg
MAC	20.05	ft

HORIZONTAL TAIL		
Area	625	ft^2
Aspect Ratio	3.37	
Sweep (0.25c)	35	deg
Taper Ratio	0.421	
Dihedral	7.0	
Tail Volume	0.638	

VERTICAL TAIL		
Area	312	ft^2
Aspect Ratio	1.46	
Sweep	31.0	deg
Taper Ratio	0.45	
Tail Volume	0.0447	

C.G. TRAVEL RANGE: 28-32% M.A.C.

ENGR.	TAYLOR	9/67	REVISED	DATE	367-80 INFLIGHT SIMULATOR TWO VIEW DRAWING	367-80 AIRPLANE
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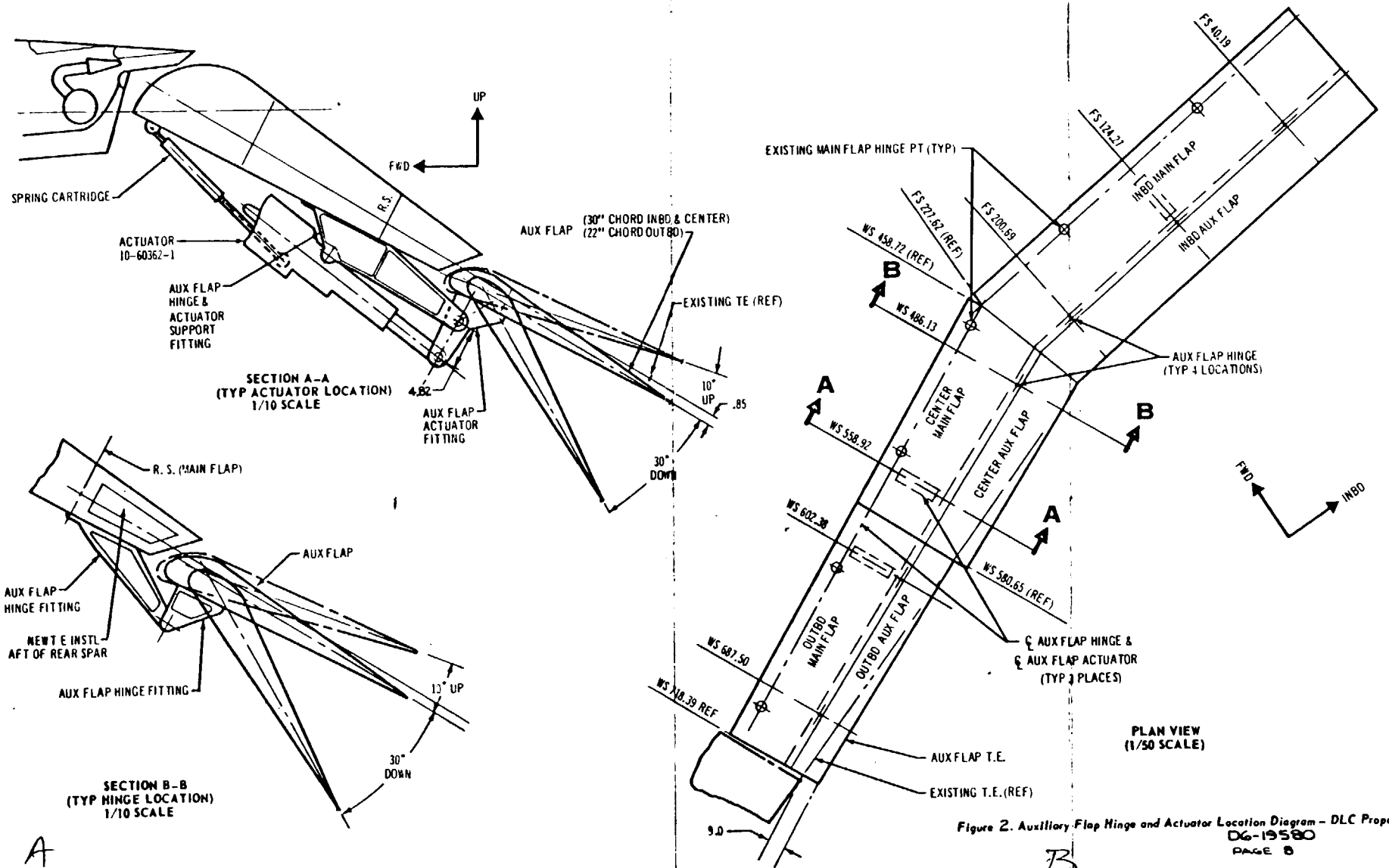


Figure 2. Auxiliary Flap Hinge and Actuator Location Diagram – DLC Proposal

3.0 FLAP SYSTEM DESIGN DETAILS

The flap configuration shown in Figure 2 has been developed during Phase I studies utilizing data derived from NASA wind tunnel tests.

The selected configuration provides a movable slotted panel (auxiliary flap), replacing the trailing edge aft of the flap rear spar, on each of the existing boundary layer control (BLC) flaps. Each auxiliary flap will be powered by a dual tandem electrohydraulic servo actuator of the type currently used on the 367-80 elevators.

The airplane left-hand hydraulic system will supply fluid to one-half of each actuator and the right-hand hydraulic system will supply fluid to the other half. With a single hydraulic system operating, actuators will remain in the null position.

Auxiliary flap position modulation will be controlled by an electrical signal from the command generation circuitry to the servo-actuator. The position command will be proportional to an input command from the pilot. Fault-detection circuitry will be provided to preclude erroneous hardover assymmetrical commands.

Auxiliary flap instantaneous surface rates of approximately 25 degrees per second or continuous rates of approximately 20 degrees per second will be available during normal operation.

3.1 Structural Rework

The structural rework required for the flap modification consists of the following items:

- o Removal of the trailing edges of all flaps aft of the flap rear spars.
- o Design, fabrication, and installation of a trailing-edge cove installation to all flaps aft of the flap rear spars.
- o Design and fabrication of six auxiliary flaps and installation on main flaps:
  - a. L.H. and R.H. inboard, approximately 221-inch span and 30.0 chord
  - b. L.H. and R.H. center, approximately 116-inch span and 30.0 chord
  - c. L.H. and R.H. outboard, approximately 140-inch span and 22.0 chord.

These flaps will be of sheet metal construction with hinge fittings and hinge backup support fittings machined from bar and plate stock.

3.2 Mechanisms

Hydraulic actuators, Dwg. No. 10-60362, will be installed on the lower side of flap for each auxiliary flap. Spring cartridges will be installed on the lower side of each main flap and attached to mechanical input lever of actuator.

3.3 Hydraulics

The hydraulic rework required consists of the following items:

- o Design, fabrication, and installation of pressure and return lines from wing spar area to each auxiliary flap actuator, actuators to be plumbed to both left- and right-hand hydraulic systems. Flexible hoses are to be used at each actuator.
- o Installation of two 25-cubic-inch accumulators in each wing. One will be installed in the left-hand system supply to the actuators, and the other in the right-hand system supply to the actuators.
- o Design, fabrication, and installation of return line oil to fuel heat-exchanger loops in the inboard fuel cell of each wing.

3.4 Electrical/Electronic System Modifications

Installation of "Direct Lift Control" on the 367-80 airplane requires the modification of two existing electrical/electronic interfaces and the addition of three new interfaces (Fig. 3). The interconnect panels of the existing interface console act as a distribution center for signal transmission. Therefore, all electrical/electronic interfaces are referenced to the interconnect panels.

3.4.1 Interconnect Panel/Actuator Interface (Fig. 4)

This is a new interface necessary to allow auxiliary flap actuator command and control at the interface console. The electrical portion of this interface consists entirely of the cable runs required to transmit solenoid valve on-off control signals and to close the servo loops of the six new actuators.

3.4.2 Interconnect Panel/Servo Electronics Interface (Fig. 5)

This is a new interface which provides the electronics necessary to close the servo loops of the auxiliary flap actuators. The primary servo loops and mod piston require a demodulator and isolation amplifier. A single summing servo amplifier is common to both loops.

3.4.3 Interconnect Panel/Logic Circuitry Interface (Fig. 6)

This is a modification of an existing interface. The purpose of this modification is to provide for failure detection in the auxiliary flap control system and on-off control of the auxiliary flap actuators.

The failure detection philosophy applied to the auxiliary flap system is aimed at providing a "fail safe" system as opposed to a "fail operational" system. Thus, a single failure in either the electronics or hydraulics

results in automatic system shutdown. The airplane control surface shutdown rate is limited by a three-way solenoid valve which switches an orifice into the return line upon shutdown. Approximately five seconds will be required for the surface to return to neutral from a hardover position. This prevents instantaneous loss of lift upon automatic shutdown. In addition to automatic shutdown, the logic circuitry will also inhibit system engagement in the event that a pre-engagement failure is present.

Auxiliary flap disengage is accomplished by de-energizing the solenoid drivers in the logic circuitry. This in turn de-energizes the solenoid valves in the actuators, removes hydraulic power from the actuator mod piston servos, and switches the restrictors into the return lines. However, this action does not remove hydraulic power from the main actuator mechanical loop. Upon de-energization, the main power loop switches to mechanical mode which drives and holds the surface to neutral.

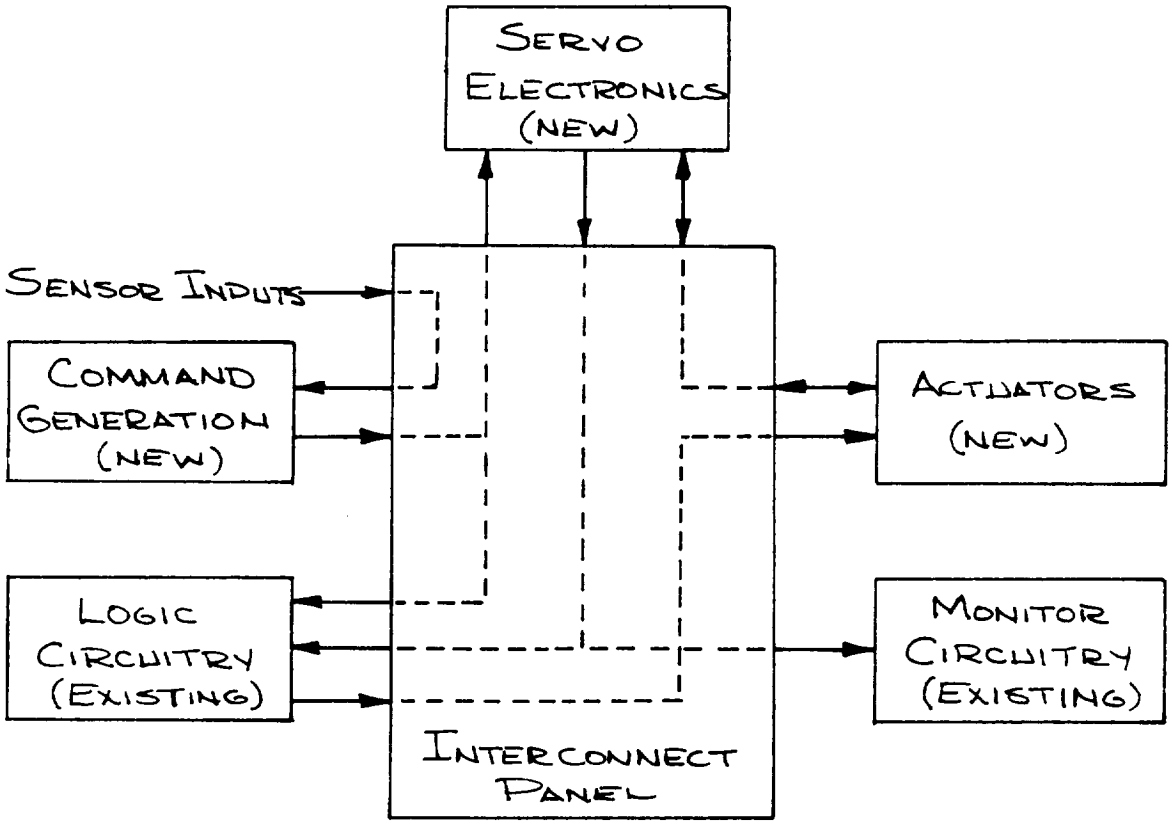
3.4.4 Interconnect Panel/Command Generation Interface (Fig. 7)

This is a new interface required to provide surface position commands for the auxiliary flap actuators. At this point, command generation techniques have not been fully defined. Thus, circuitry has been provided

with sufficient flexibility to accommodate most anticipated approaches. The circuit incorporates a summing amplifier accepting multiple inputs with independent gain control on each input and a shaping amplifier. Additional shaping can be incorporated into the summing amplifier if required. The circuit is dual redundant in that two identical circuits are provided to allow failure detection by output comparison.

3.4.5 Interconnect Panel/Monitor Circuitry Interface (Fig. 8)

This is a modification of an existing interface. The purpose of the change is to allow auxiliary flap position to be observed at the existing monitor panel. Position information is obtained by observing the demodulated main ram LVDT output of the left inboard actuator. Only one actuator is monitored since the comparators in the logic circuitry preclude system operation if specified tracking error limits are not maintained.



CALC.	CONDIT		REVISED	DATE	ELECTRICAL INTERFACES AFFECTED BY 367-80 DLC INSTALLATION	367-80 DLC
CHECK						FIG. 3
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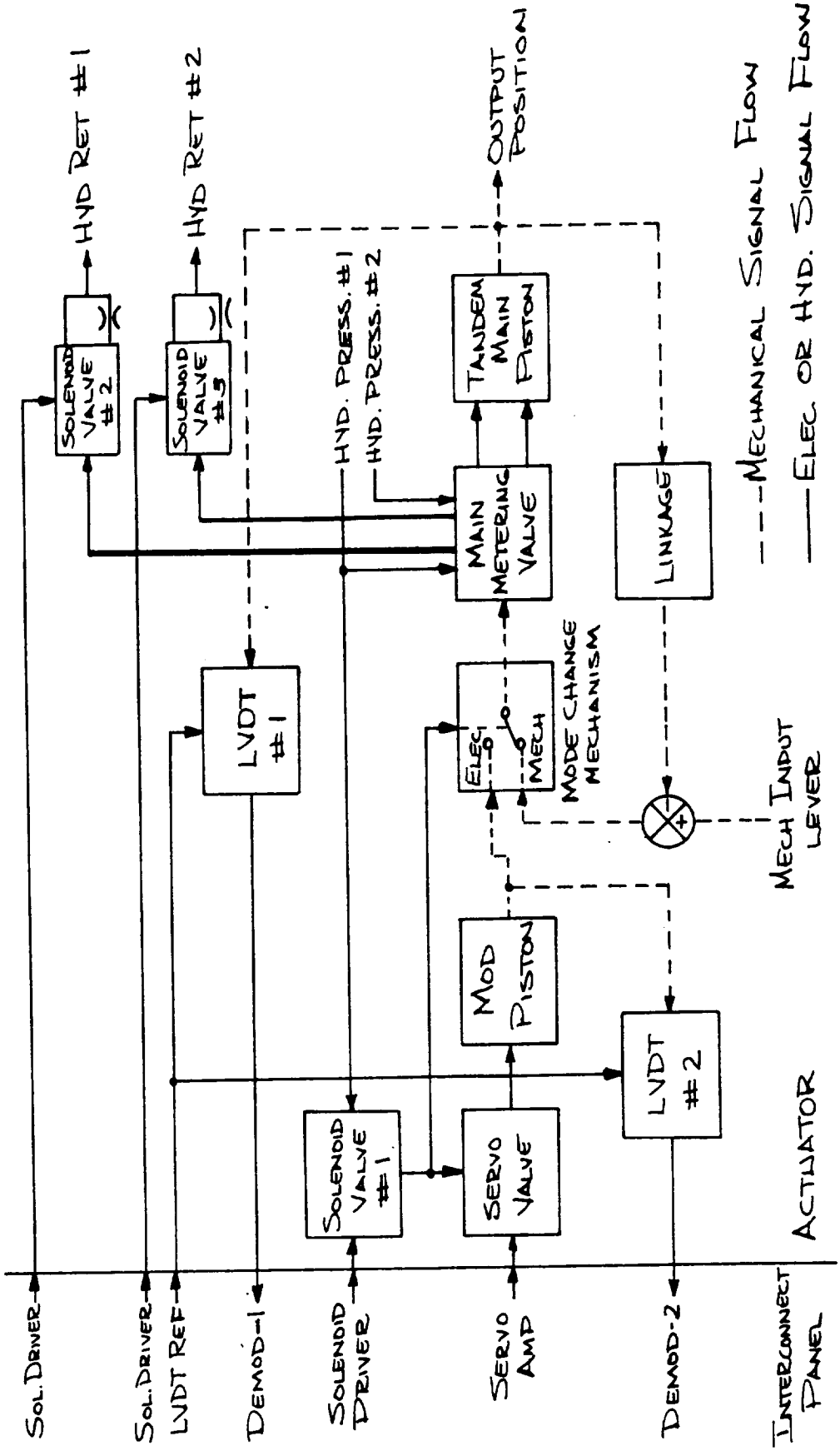

CALC.	CONDIT		REVISED	DATE	AUXILIARY FLAP ACTUATOR INTERFACE	367-80 DLC
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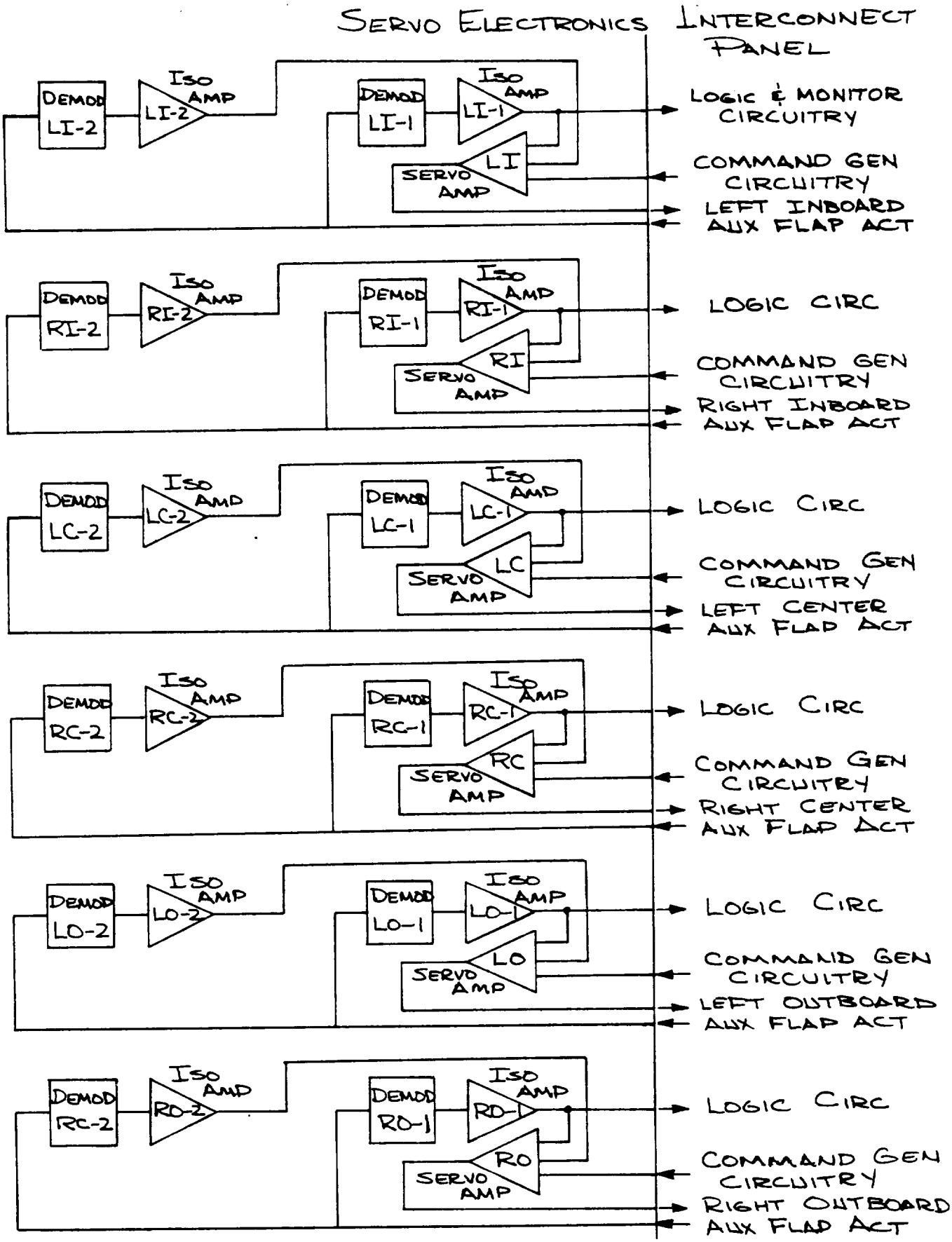

CALC.	CONDIT		REVISED	DATE	SERVO ELECTRONICS INTERFACE	367-80 DLC
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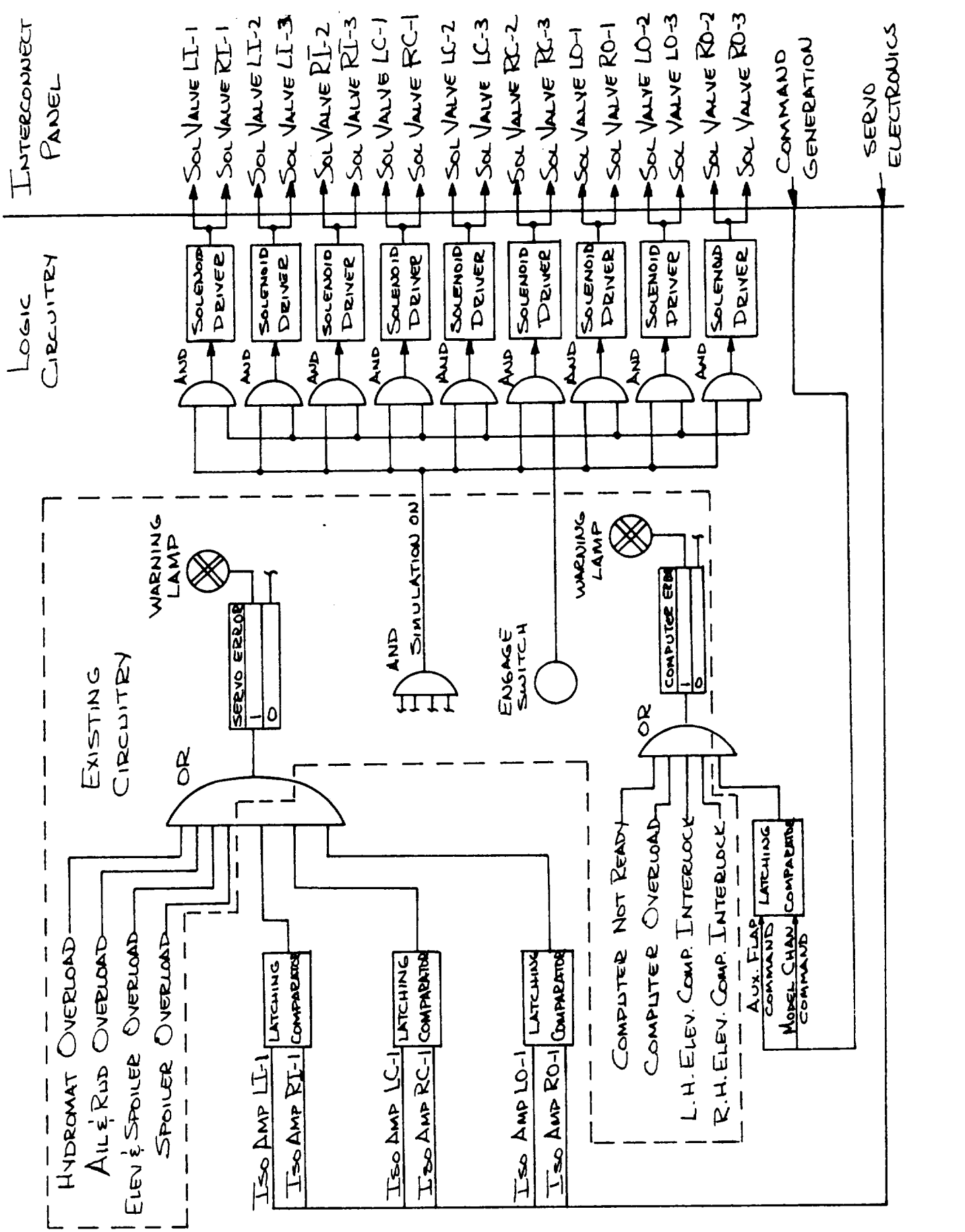

CALC.	CONDIT		REVISED	DATE	LOGIC CIRCUITRY INTERFACE	367-80 DLC
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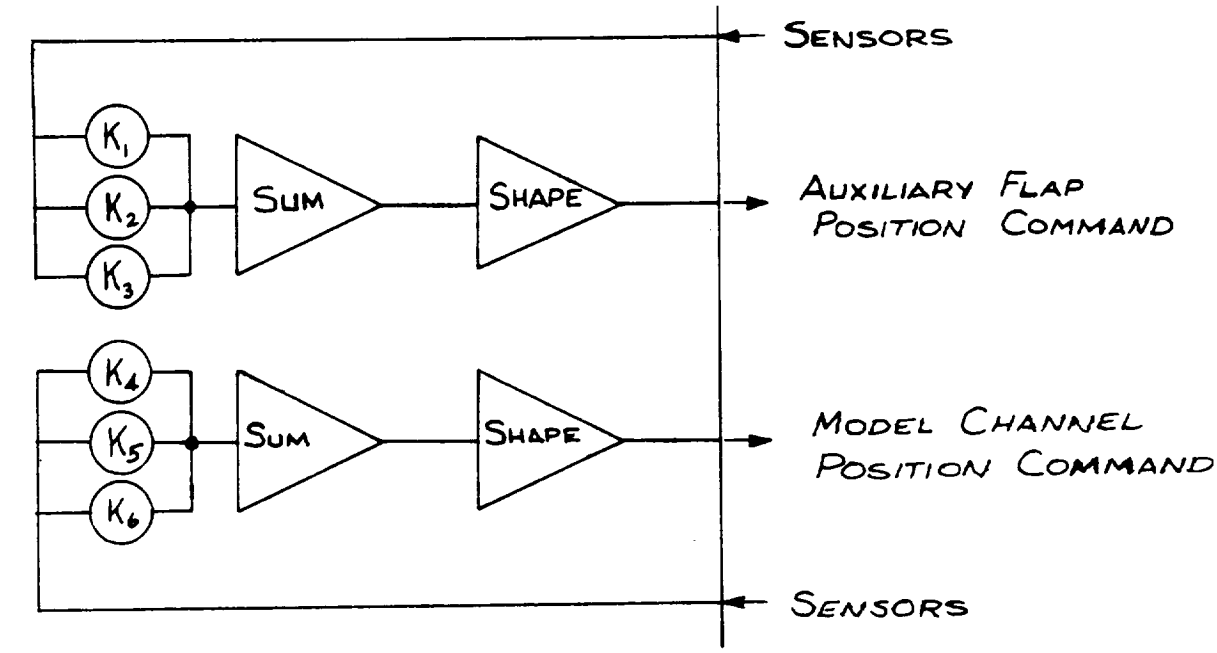
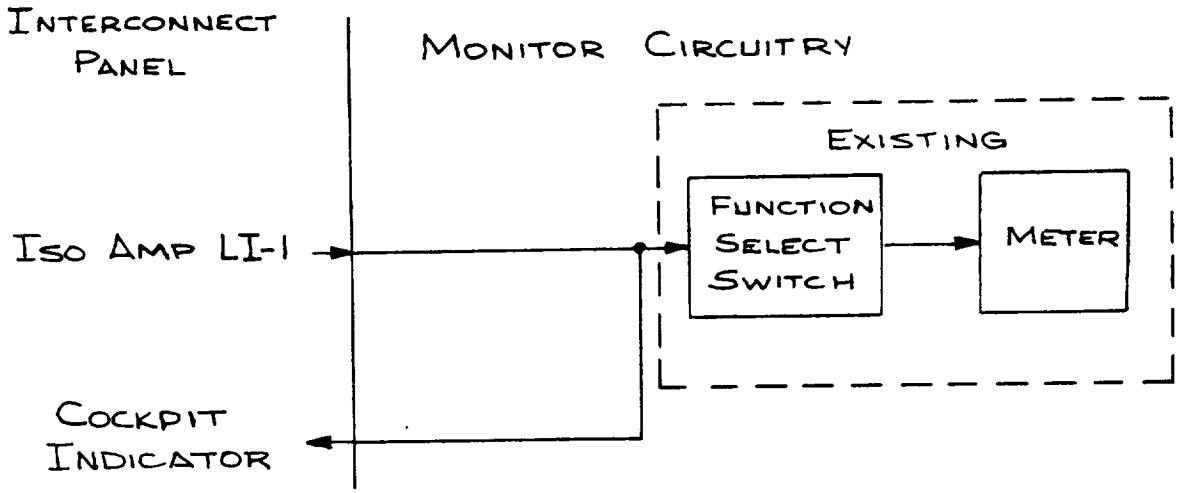


COMMAND GENERATION INTERFACE	367-80 DLC
	FIG. 7



CALC.	CONDIT		REVISED	DATE	MONITOR CIRCUITRY INTERFACE	367-80 DLC
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4.0 AUTOTHROTTLE SYSTEM

A throttle cable drum servo (Sperry P/N 6919282-111) will be installed on a sheet metal bracket below the aisle control stand and connected to the throttle lever drums by cables. An airspeed amplifier (Sperry P/N 1264-2874) will be installed in the SD-80 computer console and wiring provided between the throttle servo, airspeed amplifier and the interface. Capability will be provided to use either the throttle servo, the thrust servo or combination of both for speed control.

5.0 DESIGN ANALYSIS

5.1 Aerodynamics

This section presents the estimated aerodynamic characteristics of the 367-80 airplane with the proposed modified flap system. The predicted performance of the -80 in the DLC program was derived largely from data obtained from a NASA-Ames test in the 40' x 80' wind tunnel. This test (T-293) was a follow-on to an earlier Ames test (T-280) to select a feasible DLC flap configuration and was administered by Ames personnel with support from Boeing. Previous 367-80 wind tunnel and flight test data were also used to predict the performance.

The test model in T-293 was an approximate 1/3 scale version of the 367-80 airplane. The proposed DLC flap configuration, consisting of a slotted auxiliary aft flap for DLC and a blowing BLC main flap, was simulated on the model and closely represented the flap system to be installed on the airplane. It was felt that a reasonably accurate representation of the proposed flap design was made in Ames T-293. Therefore, the performance of the DLC auxiliary flaps shown in this section was based entirely on data from this test.

One dissimilarity between the Ames model and the actual airplane was in the vertical placement of the engines. The inboard engines on the airplane are situated so that the engine exhaust impinges directly on the trailing-edge flaps, largely

the center flap, whereas the model's engines were positioned lower beneath the wing so that there was little thrust impingement. In order to provide greater impingement on the model flaps, exhaust deflectors set at 15° up from the engine centerline were attached to the inboard engines. The anticipated performance of the auxiliary flap that follows in this section is based upon model data with the deflectors on. It is felt that the model with deflectors on is a better representation of the actual airplane with thrust impingement. A later figure will show the effect of the model deflectors on auxiliary flap lift effectiveness.

The estimated aerodynamic characteristics in this section were determined with attachment blowing on the main flap with faired aft flap. The level of blowing is based upon the blowing momentum coefficient C_{μ}. Approximate C_{μ} values for flap attachment are .014 (30° main flap), .02 (40° main flap) and .03 (50° main flap).

Four jet engines were installed on the model in T-293 to provide both thrust effects and bleed air for flap blowing. Thrust impingement effects from the inboard engines are quite significant in both main and auxiliary flap performance and are represented on the following plots in this section by the engine thrust coefficient C_T. Unless otherwise stated, all C_T values noted are for the total gross thrust of the two inboard engines only.

LIST OF SYMBOLS

C_c	FLAP CHORDWISE FORCE COEFFICIENT
C_d	FLAP SECTIONAL DRAG COEFFICIENT
C_D	TOTAL DRAG COEFFICIENT OF AIRPLANE
C_l	FLAP SECTIONAL LIFT COEFFICIENT
C_L	TOTAL LIFT COEFFICIENT OF AIRPLANE
$C_{L_{MAX}}$	MAXIMUM LIFT COEFFICIENT
C_N	FLAP NORMAL FORCE COEFFICIENT
$C_{T_{INBD}}$	INBOARD ENGINE GROSS THRUST COEFFICIENT ~ $C_T = T/qS$ (TWO ENGINE UNLESS NOTED OTHERWISE)
C_μ	FLAP MOMENTUM BLOWING COEFFICIENT
q	DYNAMIC PRESSURE ~ PSF
S	367-80 REFERENCE WING AREA ~ 2821 FT^2
W	AIRPLANE GROSS WEIGHT ~ LBS
V	EQUIVALENT AIRSPEED ~ KNOTS
V_s	1 "g" STALL SPEED ~ KNOTS
L/D	LIFT/ DRAG RATIO
T/W	NET THRUST / WEIGHT RATIO
$\Delta C_{D_{AUX}}$	DRAG COEFFICIENT INCREMENT DUE TO AUX. FLAP DEFLECTION
$\Delta C_{L_{AUX}}$	LIFT COEFFICIENT INCREMENT DUE TO AUX. FLAP DEFLECTION

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LIST OF SYMBOLS (CONTINUED)

$\Delta C_{M_{AUX}}$	PITCHING MOMENT COEFFICIENT INCREMENT DUE TO AUX. FLAP DEFLECTION
$\Delta C_{L_{DLC}}$	TOTAL CHANGE IN LIFT COEFFICIENT FROM -10° AUX. FLAP TO 30° AUX. FLAP (TOTAL ANGULAR TRAVEL)
Δg	INCREMENTAL ACCELERATION NORMAL TO FLIGHT-PATH (NON-DIMENSIONALIZED)
b	WING SPAN ~ 130 FT (367-80)
y	SPANWISE STATION ($y = 0$ @ BODY $\mathcal{L}$)
MAC	MEAN AERODYNAMIC CHORD ~ 240.65 INCHES (367-80)
g	ACCELERATION DUE TO GRAVITY ~ 32.174 FT/SEC^2
α	WING ANGLE OF ATTACK ~ DEGREES (2° INCIDENCE WITH BODY)
γ	FLIGHT PATH ANGLE ~ DEG.
η	$2y/b$
δ_{AUX}	AUXILIARY FLAP DEFLECTION ~ DEG. (POSITIVE DOWN)
δ_{MAIN}	MAIN FLAP DEFLECTION ~ DEG.
δ_e	ELEVATOR DEFLECTION ~ DEG.

ENGR.	TAYLOR		REVISED	DATE	(CONTINUED) LIST OF SYMBOLS FOR AERODYNAMICS SECTION	TABLE 1
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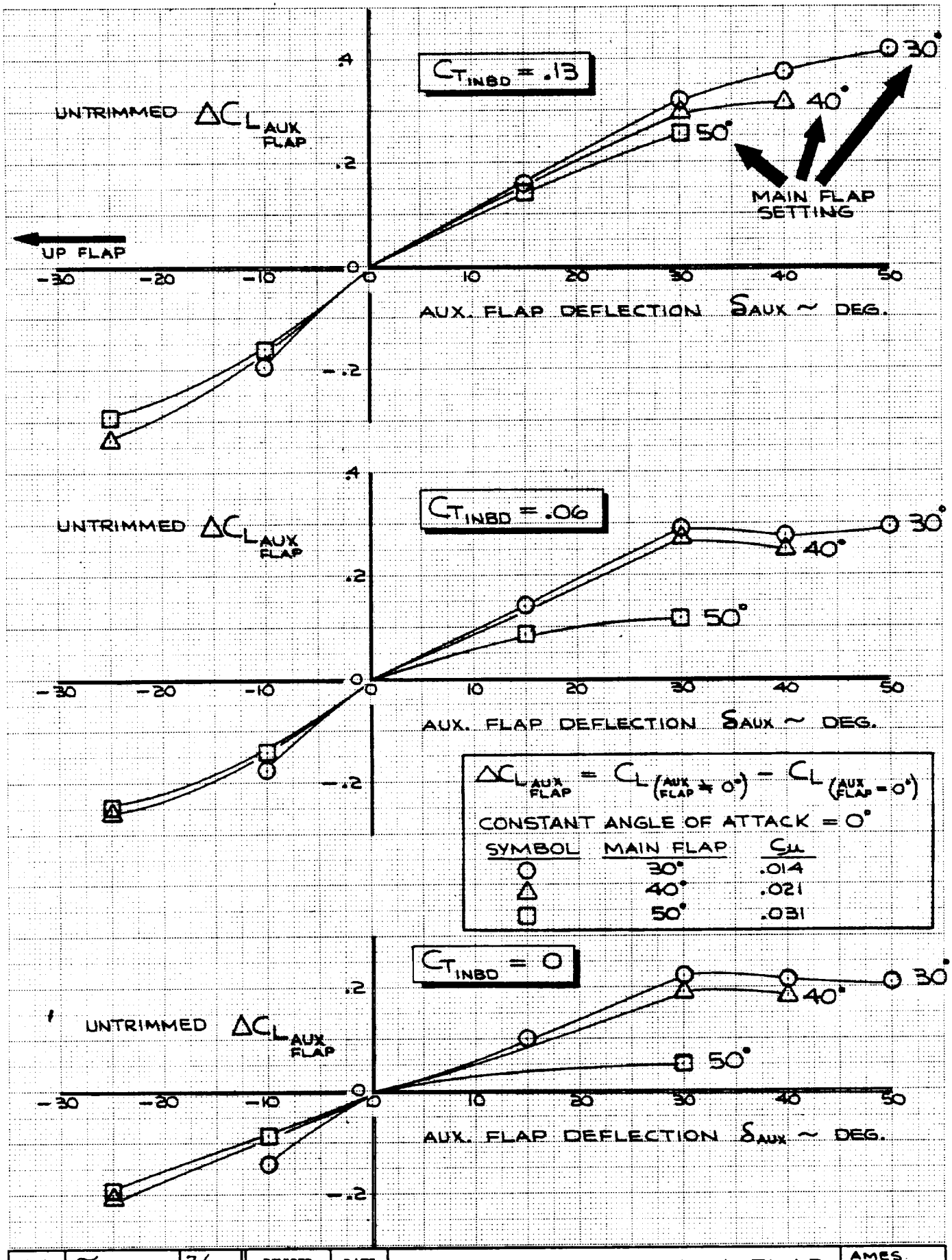
Table 1 gives a list of the symbols used in this section.

5.1.1 Performance

AUXILIARY FLAP LIFT EFFECTIVENESS: Figure 9 shows the untrimmed auxiliary flap lift effectiveness at 0° angle of attack for 30°, 40° and 50° main flap settings with attachment flap blowing. The data is presented for three values of inboard engine thrust coefficient. The ΔC_L shown on the plot is the lift change available from DLC through deflection of the auxiliary flaps with no trim effects included. It may be noted that the lift effectiveness of the auxiliary flaps is reduced with increasing main flaps and/or decreasing inboard thrust. Higher main flap deflections cause earlier separation over the auxiliary flaps while lower inboard thrust reduces impingement effects on the center and inboard auxiliary flaps. Lift effectiveness at 30° and 40° main flaps shows little difference; however, effectiveness at 50° flaps is reduced considerably and appears to fall short of program requirements except at high inboard thrust settings. It may be noted that data was obtained at auxiliary flap deflections outside the proposed deflection range of $+30^{\circ}$ (down) and -10° (up). Load limitations preclude a higher range of travel for the auxiliary flaps.



$\Delta C_{L_{AUX\ FLAP}} = C_{L_{(AUX\ FLAP\ \neq\ 0°)}} - C_{L_{(AUX\ FLAP\ =\ 0°)}}$

CONSTANT ANGLE OF ATTACK = 0°

SYMBOL	MAIN FLAP	C_μ
○	30°	.014
△	40°	.021
□	50°	.031

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UNTRIMMED AUXILIARY FLAP LIFT EFFECTIVENESS AT 0° WING ANGLE OF ATTACK

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AMES T-293 367-80

FIG. 9

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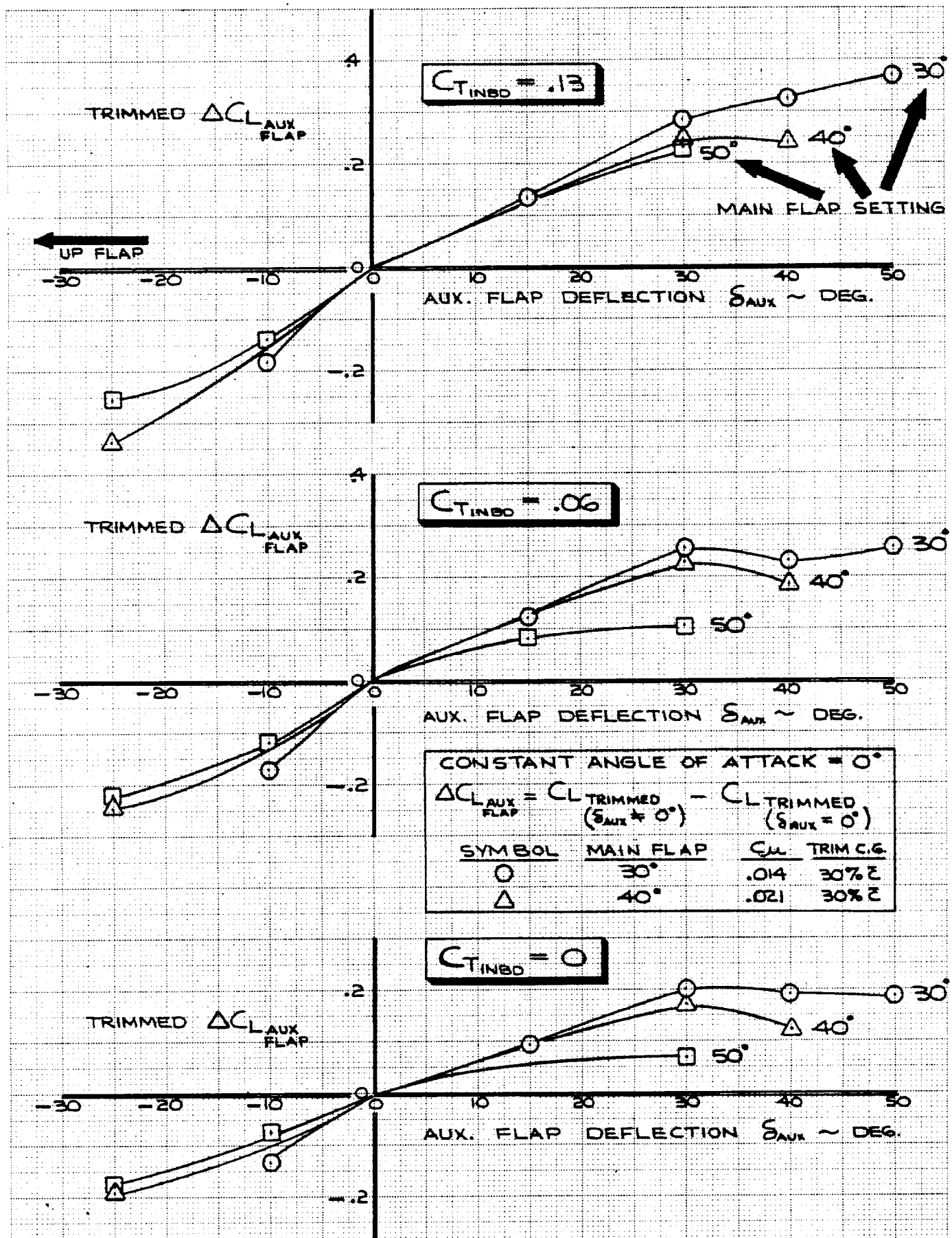
The data in Figure 9 is at a constant angle of attack of 0° with attachment flap blowing. Additional data at flaps 50° with blowing lower than attachment (C_{μ} = .02) showed virtually no change in lift effectiveness. There is also little or no change in effectiveness at other angles of attack up to 6°, which represents the approach α range.

Figure 10 is similar to Figure 9 except that the pitching moment change with auxiliary flap deflection has been trimmed out to 30% MAC. This results in less ΔC_L available for DLC since part of the lift change is lost in trimming. The data indicates that trim losses are higher at 30° and 40° main flaps.

Figure 11 presents a direct comparison of trimmed and untrimmed auxiliary flap lift effectiveness at 30° and 40° main flaps with a nominal inboard C_T of .06. The data shows that about 10% of ΔC_L is lost due to trim effects.

DRAG CHANGE WITH AUXILIARY FLAP DEFLECTION: Figure 12 presents the drag change with auxiliary flap deflection at 0° angle of attack and three inboard thrust settings. Data at main flap settings of 30°, 40° and 50° is shown. The change in drag is similar to the lift change in that down auxiliary flap gives increased drag while up flap



CONSTANT ANGLE OF ATTACK = 0°

$\Delta C_{L_{AUX\ FLAP}} = C_{L_{TRIMMED\ (\delta_{AUX} \neq 0°)}} - C_{L_{TRIMMED\ (\delta_{AUX} = 0°)}}$

SYMBOL	MAIN FLAP	C_{μ}	TRIM C.G.
○	30°	.014	30% $\bar{c}$
△	40°	.021	30% $\bar{c}$

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TRIMMED AUXILIARY FLAP LIFT EFFECTIVENESS AT 0° WING ANGLE OF ATTACK

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AMES T-293 367-80

FIG. 10

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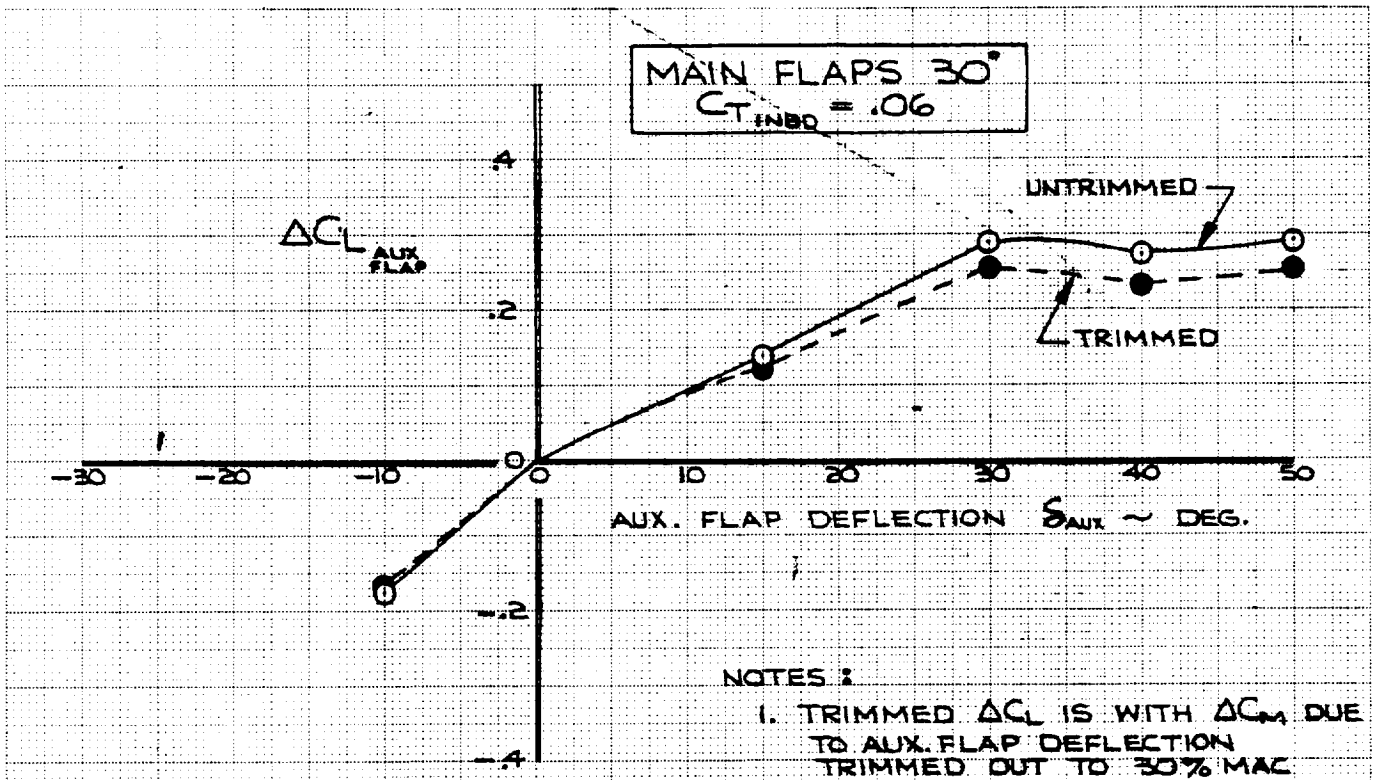
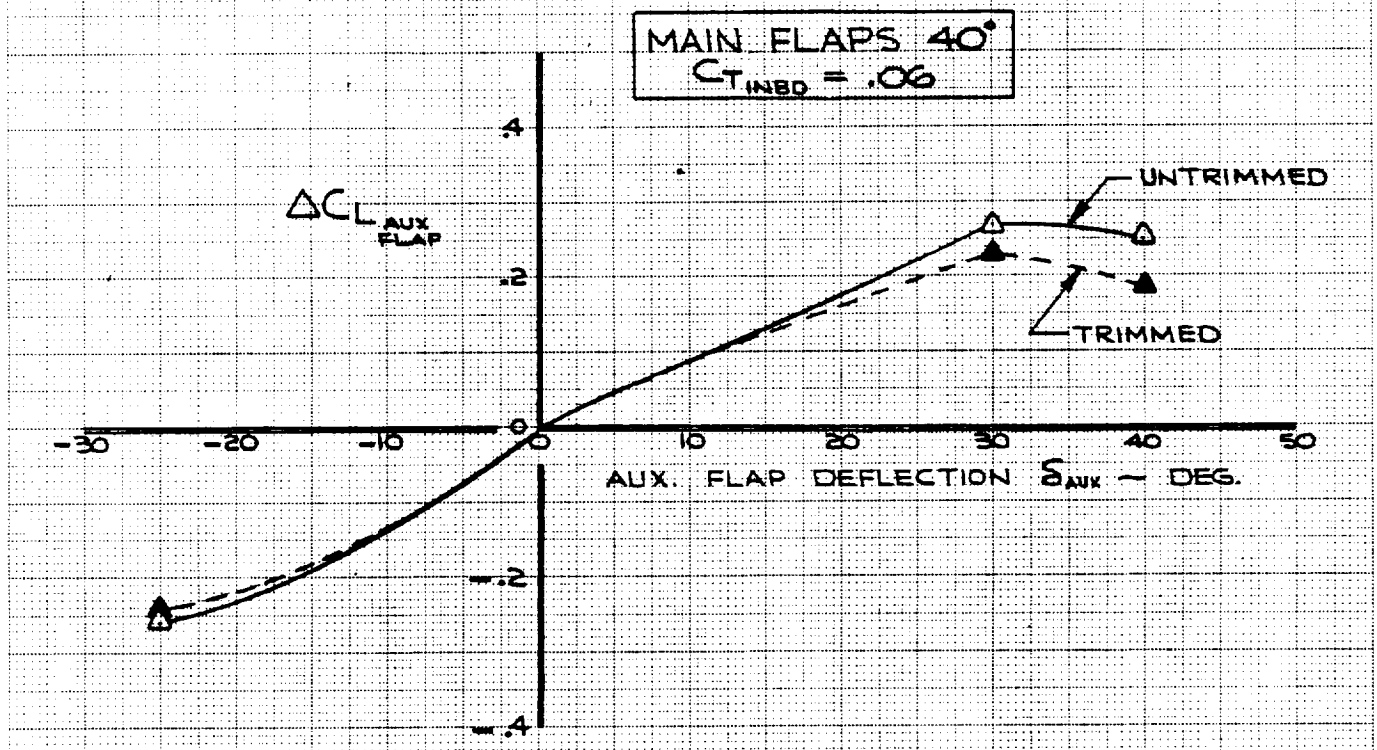


NOTES :

1. TRIMMED ΔC_L IS WITH ΔC_M DUE TO AUX. FLAP DEFLECTION TRIMMED OUT TO 30% MAC
2. ATTACHMENT BLOWING ON MAIN FLAPS
3. DATA AT 0° CONSTANT α



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COMPARISON OF TRIMMED & UNTRIMMED AUXILIARY FLAP LIFT EFFECTIVENESS
30° & 40° MAIN FLAPS C_T = .06

AMES T-283
367-80
FIG. 11

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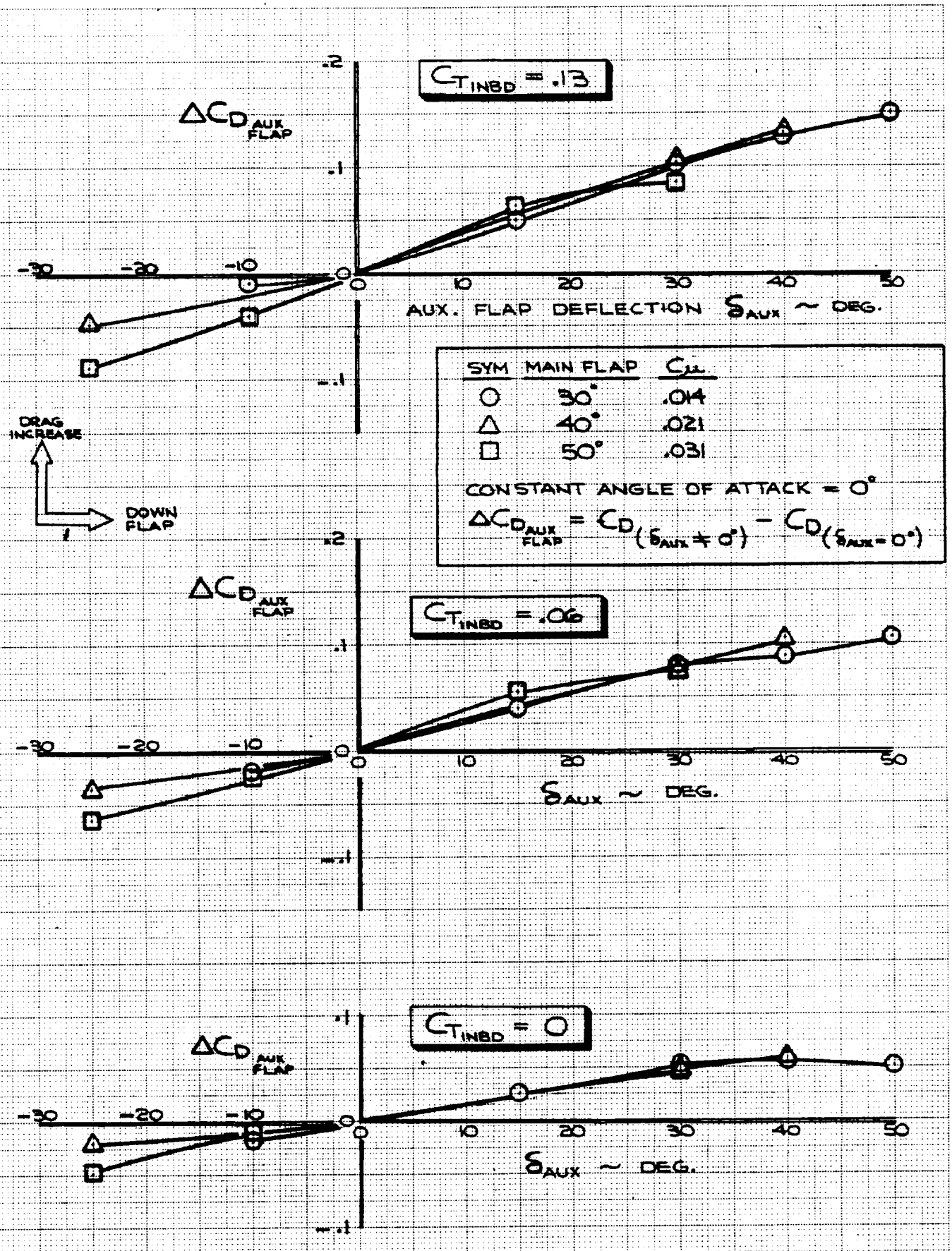
shows decreased drag. From the standpoint of flight path control, this is opposite to the desired effect of having a drag decrease accompany a lift increase, such as shown by a spoiler type DLC system. This will be covered more thoroughly later.

It may be seen from Figure 12 that the drag change, although not varying greatly with main flap setting, is significant. For instance, 30° down auxiliary flap at 130 knots would require some 8,000 to 16,000 lbs additional thrust, depending on the inboard C_T, to maintain constant speed. This is equivalent to some 5° to 10° of incremental clamshell door angle per engine.

DESCENT ANGLE VARIATION: Figure 13 shows flight path angle variation with auxiliary flap deflection for two T/W values (.05 and .10). Since lift and drag changes associated with auxiliary flap deflection are a function of inboard thrust, the curves in Figure 13 were determined for a representative 367-80 flight condition of 150,000 lbs gross weight and 125 knots with four engine thrust symmetrical across the board. This results in inboard C_T values of .025 and .05 for T/W's of .05 and .10 respectively. Figure 10 and 12 were used in conjunction with flight-test values of the 367-80 airplane to obtain the flight path variation.



CALC	TAYLOR	8/67	REVISED	DATE	DRAG CHANGE WITH AUXILIARY FLAP DEFLECTION AT $\alpha = 0°$
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367-80
FIG. 12
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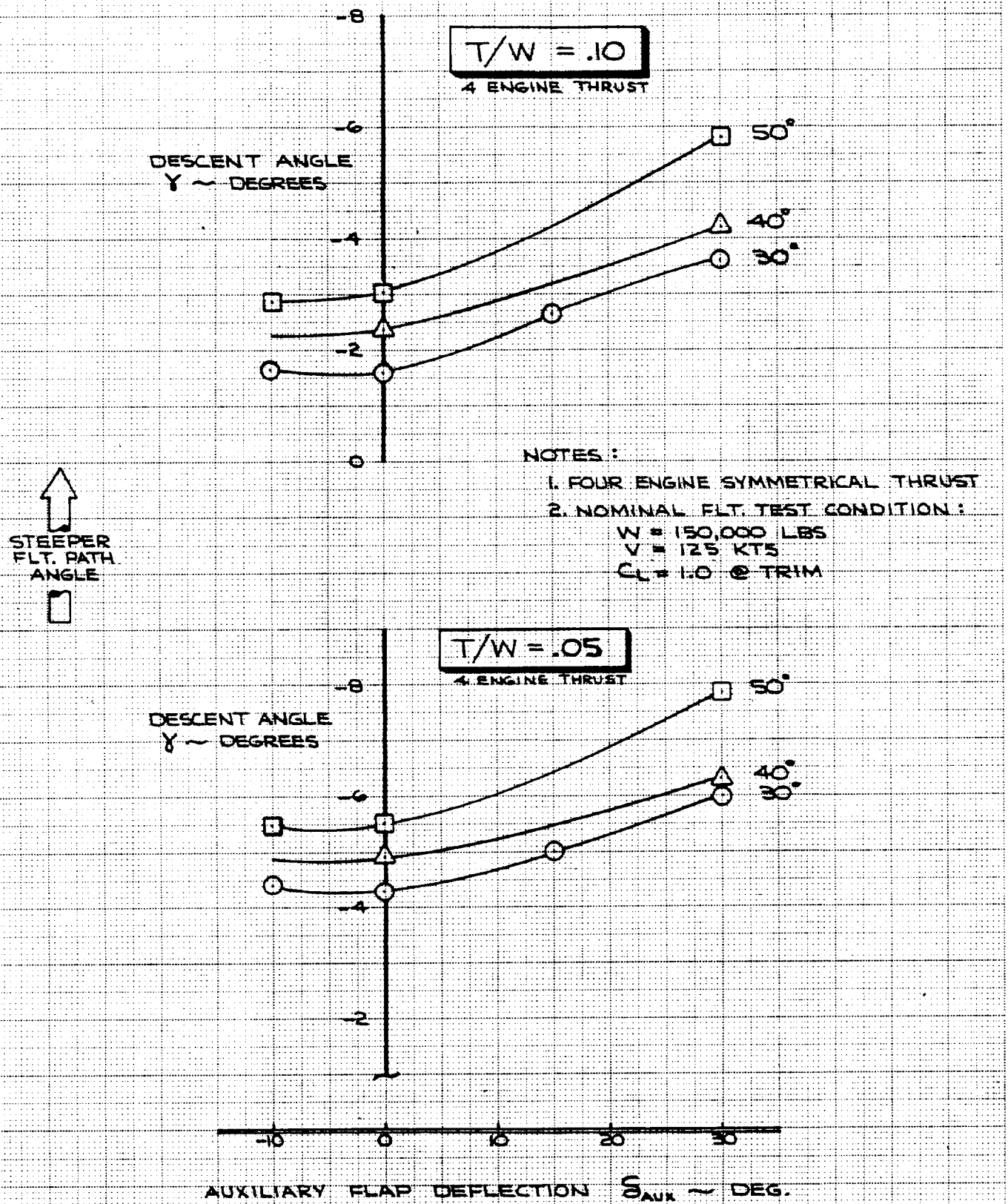
As noted earlier, the drag change characteristics with auxiliary flap deflection are undesirable from the standpoint of flight path control. This effect may be noted in Figure 13. There is virtually no change in descent flight path with -10° up auxiliary flap; however, with full down flap (30°), the descent angle steepens some 2° or so, which is opposite to the desired effect. When the pilot is below his target approach glide slope, it is to his advantage to have down flap deflection produce not only increased lift but also a shallower flight path. This will require some form of drag control, such as the auto-throttle. Although the auto-throttle is primarily a speed control device, it will also function to prevent or reduce "wrong way" descent angle variations as noted in Figure 13.

It might be of interest to note that a $\Delta\gamma$ of -2° represents about .035 g's longitudinal acceleration and about 8° incremental clamshell door angle.

L/D's FOR FLIGHT-PATH CONTROL: Figure 14 shows the required and available lift/drag ratios of the -80 at various inboard thrust coefficients for flight path angles of 0° (level flight), -3°, -6° and -9° (descent flight). The available L/D's were obtained from actual 367-80 flight data at main flap settings of 30° and 50°



CALC	TAYLOR	8/67	REVISED	DATE	DESCENT ANGLE VARIATION WITH AUXILIARY FLAP DEFLECTION FOR T/W'S OF .05 AND .10
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FIG. 13
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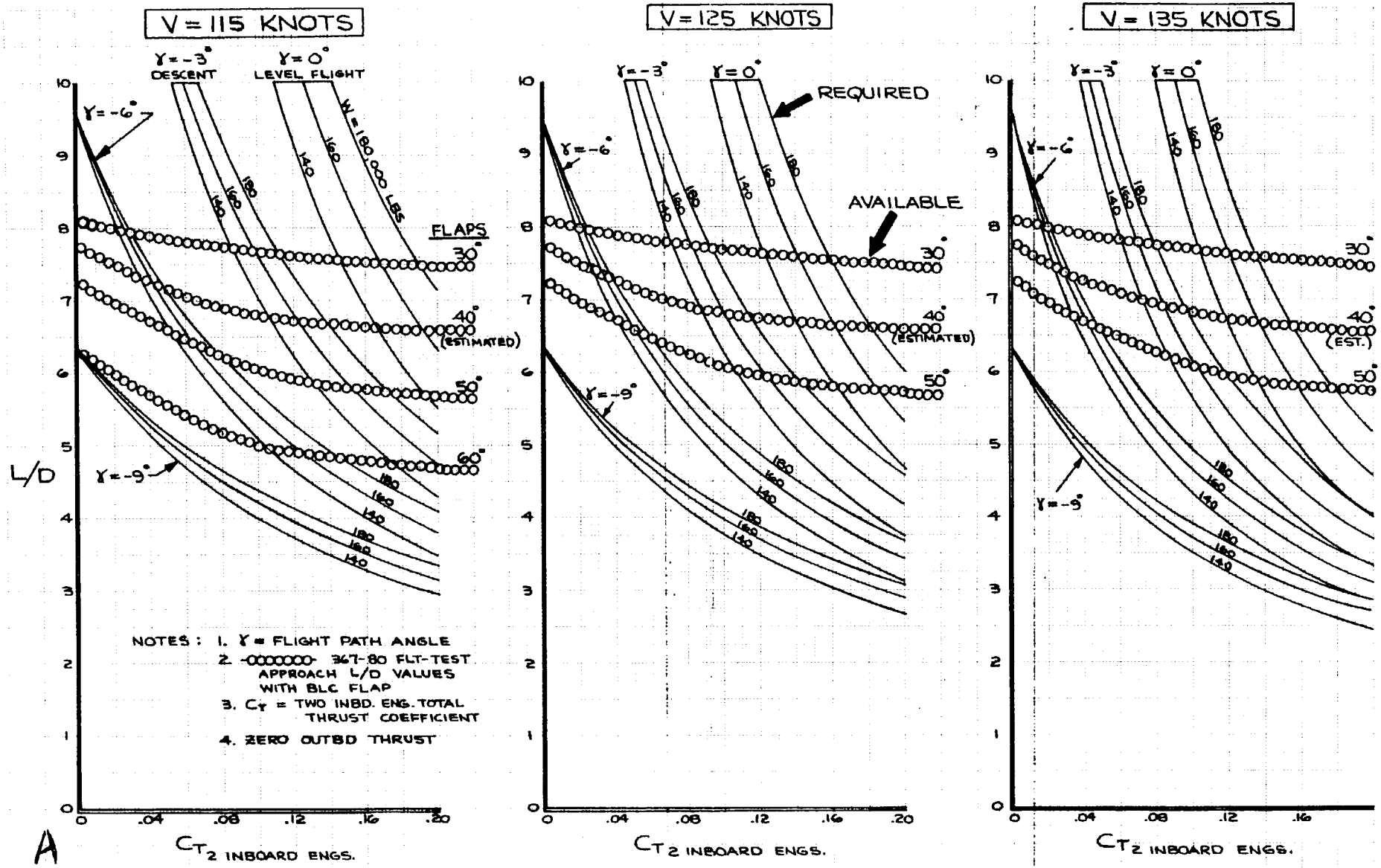

CALC	TAYLOR	6/20/7	REVISED	DATE	REQUIRED L/D VS INBD. C_T FOR VARIOUS FLT. PATH ANGLES WITH AVAILABLE 367-80 L/D	367-80 FIG. 14
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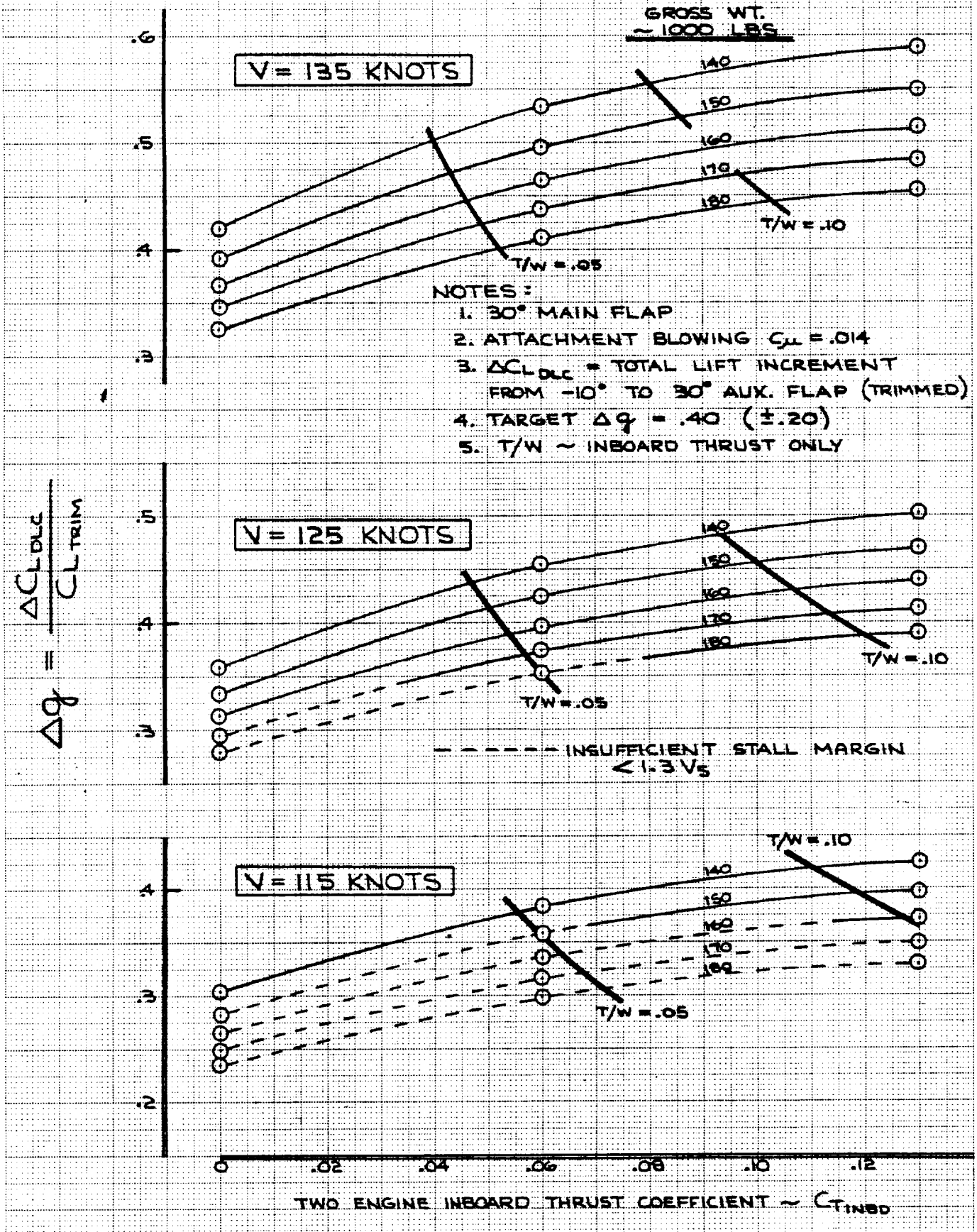
(no auxiliary flap). An estimated flaps 40° line is also shown. The required L/D's are based upon zero outboard engine thrust. Three speeds are shown since thrust is a function of both speed and thrust coefficient. This figure may be used in conjunction with Figure 13, which shows descent angle with auxiliary flap deflection, to determine the flight path capability for steep approach work.

NORMAL ACCELERATION: Incremental "g"s available from the auxiliary flaps are shown in Figures 15 and 16 for main flap settings of 30° and 40° respectively. The Δg values were obtained by dividing the total trimmed lift increment due to auxiliary flap deflection (from -10° up-flap to 30° down-flap) by the trim lift coefficient for each speed and weight. Trimmed lift changes from auxiliary flap deflection were shown previously in Figure 10. Since the lift effectiveness of the auxiliary flaps is a function of inboard thrust, the Δg values are plotted against inboard C_T. It should be noted that the Δg's shown represent the total available Δg, i.e., a Δg of .40 represents $\pm$.20, a Δg of .30 represents $\pm$.15, etc.

The dashed lines on Figures 15 and 16 indicate insufficient stall margin (< 1.3Vs). The $C_{L_{max}}$ values used to calculate these limits were obtained from previous



CALC	TAYLOR	8/67	REVISED	DATE	Δq AVAILABLE WITH AUXILIARY FLAP DEFLECTION @ 30° MAIN FLAP
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FIG. 15
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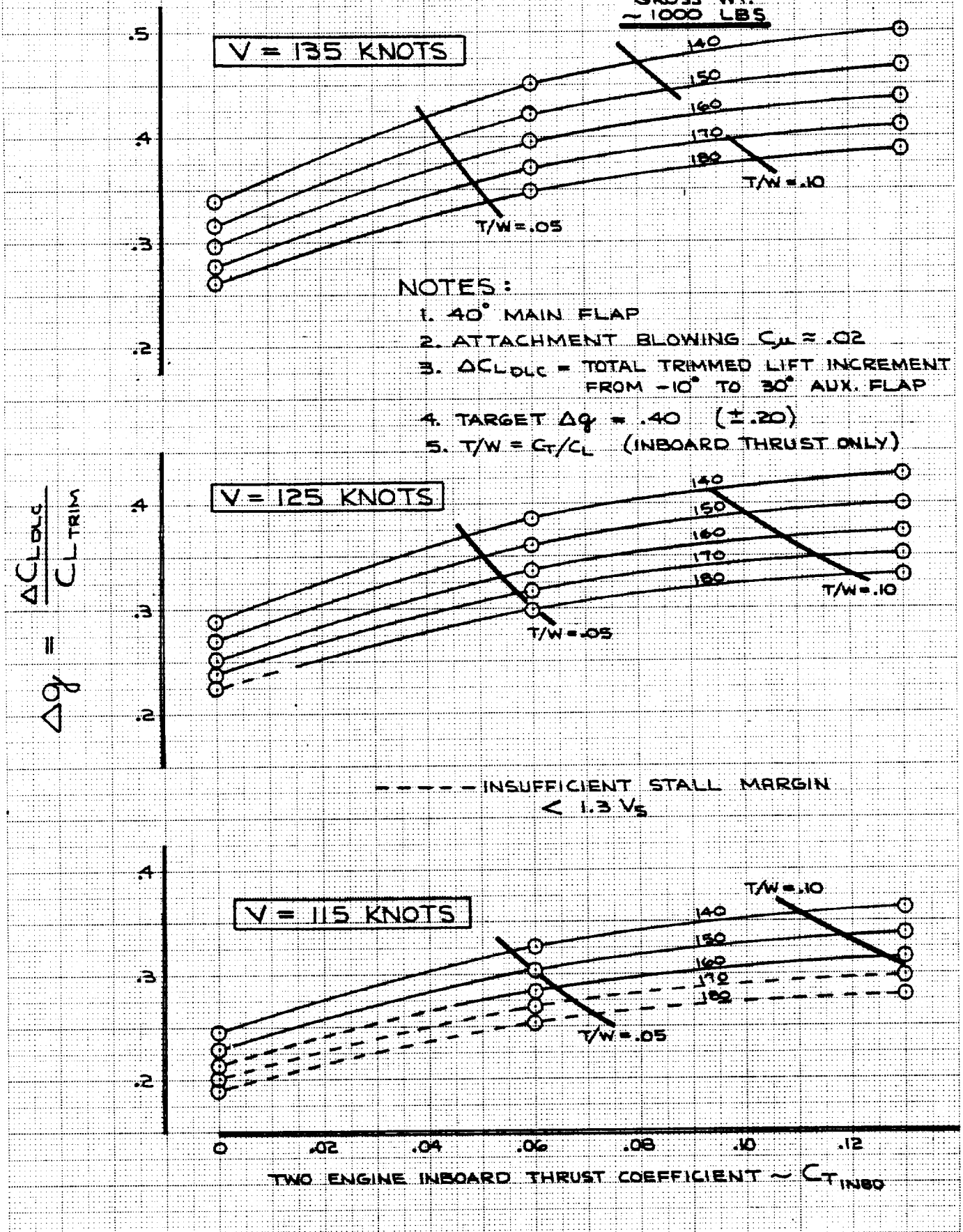

CALC	TAYLOR	8/67	REVISED	DATE	Δq AVAILABLE WITH AUXILIARY FLAP DEFLECTION @ 40° MAIN FLAP
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367-80
FIG. 16
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367-80 flight data and were based on main plus faired auxiliary flap with attachment blowing. The maximum lift coefficients were not held constant with flap setting but were allowed to vary with inboard thrust settings. If sufficient bleed air is available, it might be feasible to increase maximum lift through higher flap blowing with little, if any, change in auxiliary flap effectiveness. This would permit higher gross weights to be tested within stall margin limitations.

It may be seen from Figures 15 and 16 that the target Δg of .40 ($\pm$.20) is not met at the 115 knot speed. At 125 knots, the available Δg is below target except in the lower weight range and/or high thrust region. Target Δg is met or exceeded for most weight and thrust conditions at 135 knots.

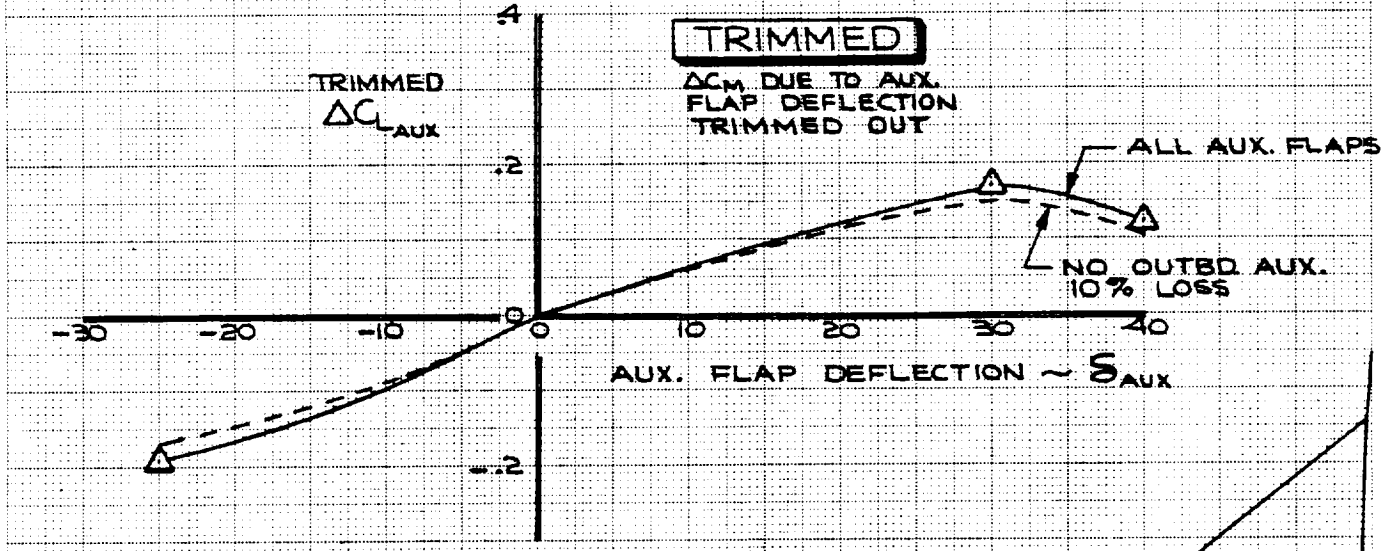
The available Δg at 50° main flaps is not shown. However, due to poor auxiliary flap lift effectiveness at this flap setting, the target Δg of $\pm$.20 is met only at the 135 knot condition at weights less than 160,000 lbs. with high inboard thrust.

INOPERABLE OUTBOARD AUXILIARY FLAP: The effect of deleting the outboard auxiliary flap on the lift effectiveness of the auxiliary flaps is shown in Figure 17 for 40° main

flap and zero inboard thrust. Both trimmed and untrimmed curves are shown and are compared to the case where all three flap segments (inboard, center and outboard) are in operation.

The lift effectiveness of the auxiliary flaps without the outboard auxiliary flap was obtained by estimation. This was due to lack of wind tunnel data for this particular configuration. Data was available for the inboard auxiliary flap only but not for the inboard plus center flap configuration. The untrimmed lift effectiveness was obtained by resolving the total auxiliary flap lift of the three flap segments into lift per segment from a consideration of individual auxiliary flap areas. The effect of the lower trailing-edge sweep angle on the inboard flap was also included. Using this method, it was estimated that the inboard auxiliary flap carried 57% of the total auxiliary flap lift, the center flap 25% and the outboard flap 18%. Inboard auxiliary flap effectiveness from this method checks reasonably well with the wind tunnel data. All-flap lift effectiveness was therefore reduced 18% to account for a locked-out outboard flap.

To estimate the trimmed performance, the estimated outboard auxiliary flap lift increment was used in conjunction

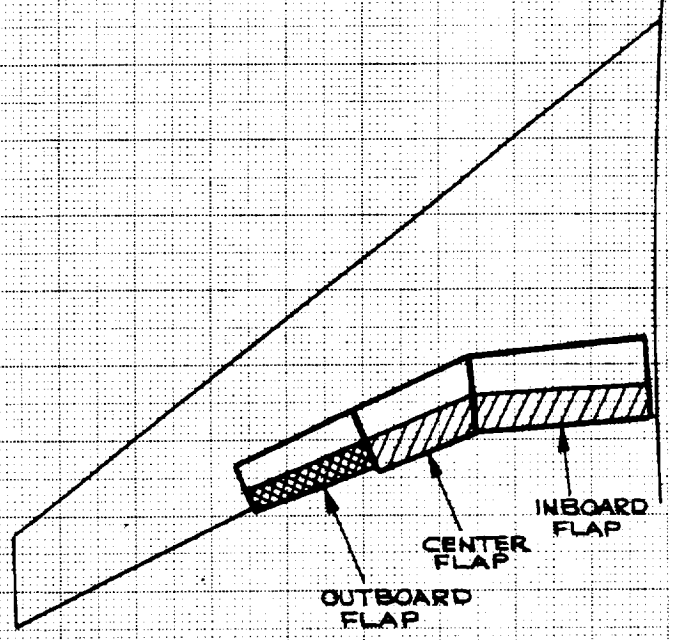


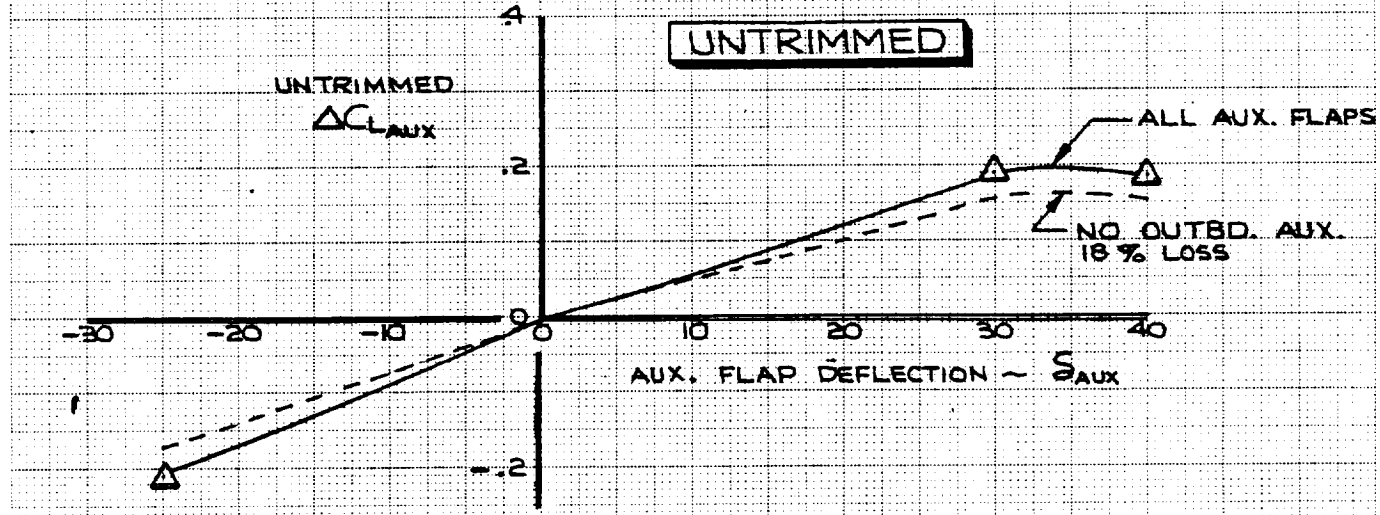
NOTES:

1. 40° MAIN FLAPS
2. INBD $C_T = 0$
3. CONSTANT $\alpha = 0°$

——— ALL AUX. FLAPS OPERATING

- - - - - INBOARD & CENTER FLAPS OPERATING ~ OUTBOARD AUX. FLAP INOPERABLE (ESTIMATED)





CALC	TAYLOR	8/67	REVISED	DATE	EFFECT OF NOT OPERATING THE OUTBOARD AUXILIARY FLAP ON AUX. FLAP LIFT EFFECTIVENESS
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367-80
FIG. 17
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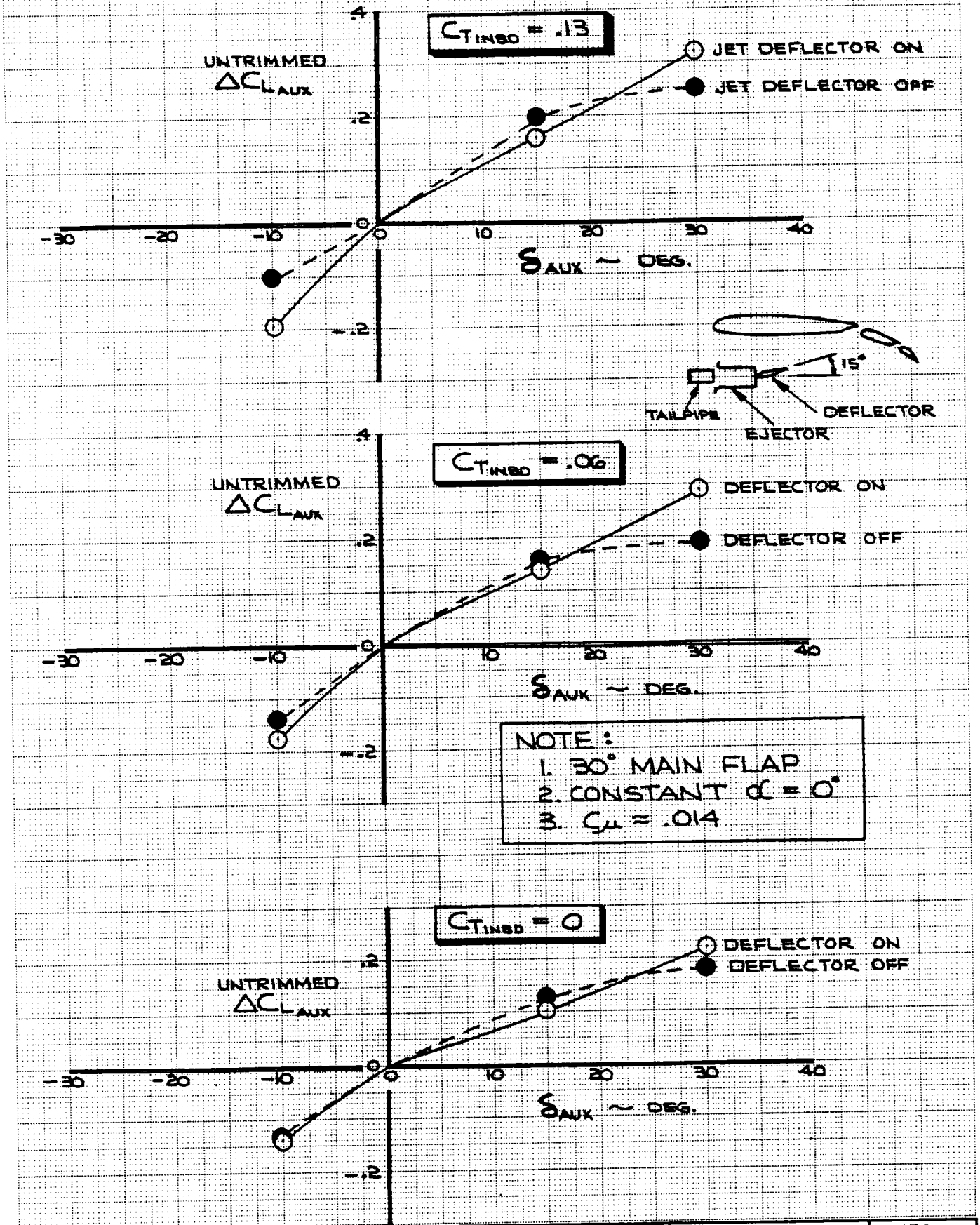
with estimated center of pressure to determine the pitching moment contribution of the outboard flap. Downwash effects were assumed to be negligible as the outboard flap lies outboard the horizontal tail tip. With no outboard flap, there is less pitching moment due to auxiliary flap deflection to trim out. On this basis, the 18% lift loss due to an inoperable outboard auxiliary flap is reduced to 10% when trim effects are considered.

INBOARD ENGINE EXHAUST DEFLECTORS: As noted earlier, the anticipated performance of the proposed DLC flap system was based on model data with exhaust deflectors on the inboard engines. Figure 18 shows the effect of the deflectors on auxiliary flap lift effectiveness with 30° main flap. It may be seen that lift effectiveness is reduced with deflectors off and that this reduction, as expected, becomes greater at higher thrust settings. The decrease in overall auxiliary flap lift is about 30% at $C_T = .13$. However, the -80 shouldn't show as great a degradation because of more direct thrust impingement from the inboard engines. At present, deflectors are not being proposed for the airplane because of assorted problems, such as underwing temperature considerations.

AUTO-THROTTLE REQUIREMENTS: Auto-throttle requirements will be determined during initial flight testing of the



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EFFECT OF EXHAUST DEFLECTOR ON AUX FLAP LIFT EFFECTIVENESS 30° MAIN FLAP

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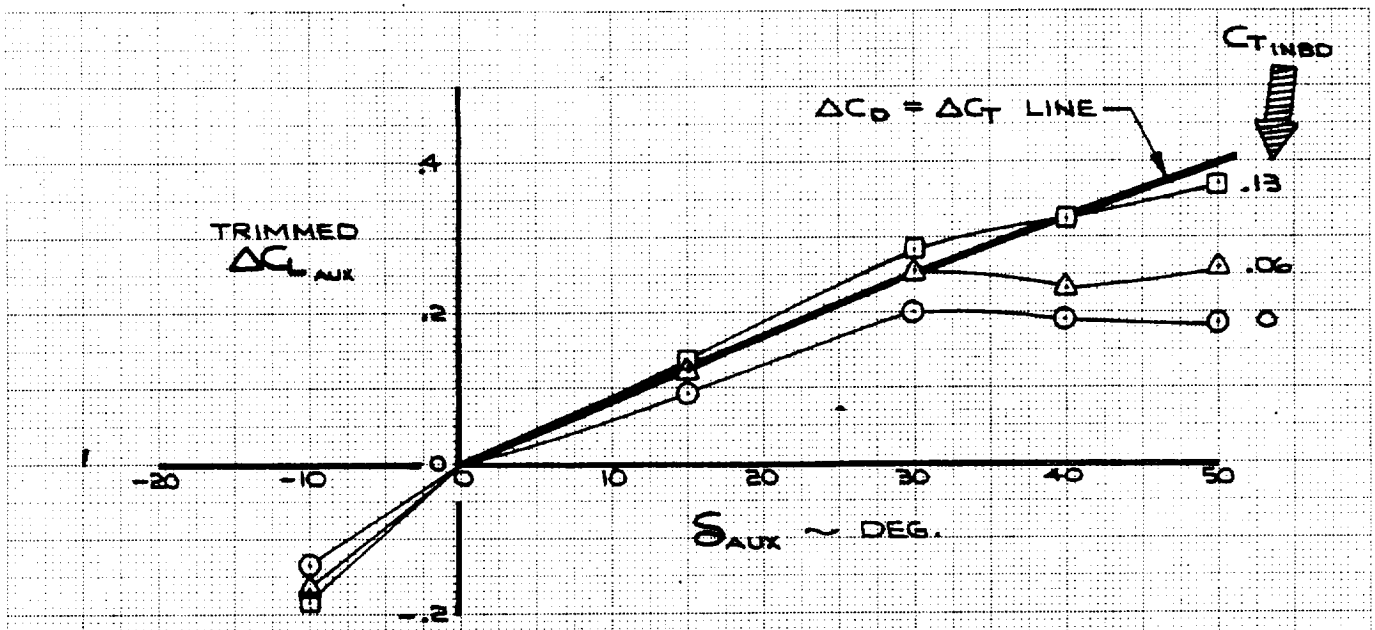
DLC flap system. However, preliminary requirements will be determined from wind tunnel data. Figure 19 shows such an example. Drag changes with auxiliary flap deflection for several valves of inboard thrust coefficient are shown on the lower plot. The heavy line shows the curve where $\Delta C_D = \Delta C_T$. The dashed line is a linear approximation of the $\Delta C_D = \Delta C_T$ curve. $\Delta C_T / \delta_{aux}$ for this dashed line is about .0028/degree.

A supplemental feature of the auto-throttle will be additional normal acceleration (Δg) for flight path control. This is due to the increased lift effectiveness of the auxiliary flaps with increasing thrust, as seen in the upper plot of Figure 19.

5.1.2 Stability and Control

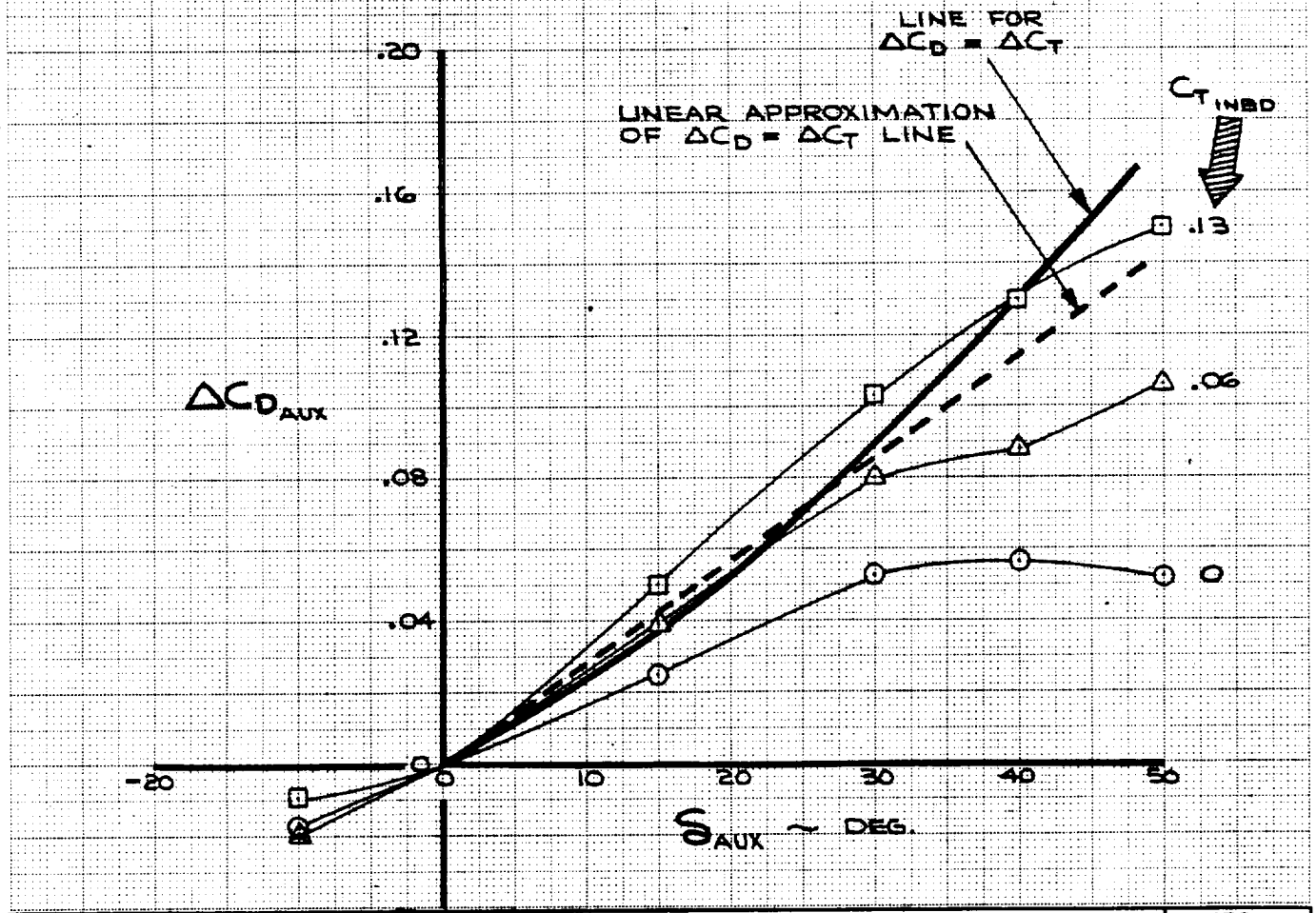
PITCHING MOMENT CHANGE: Pitching moment changes associated with auxiliary flap deflection are shown in Figure 20. The ΔC_M arises from a change in both auxiliary flap lift and downwash over the tail. Elevator deflections required to trim out these pitch changes are also noted.

Only data at 30° and 40° main flap settings and at C_T's of 0 and .06 are shown. This was because other pitching moment data appeared inconsistent and open to



NOTES :

1. 30° MAIN FLAPS
2. ATTACHMENT $C_\mu \approx .014$
3. CONSTANT $\alpha = 0°$



CALC	TAYLOR	8/67	REVISED	DATE	AUTO-THROTTLE REQUIREMENTS 30° MAIN FLAPS	AMES T-293 367-80 FIG. 19
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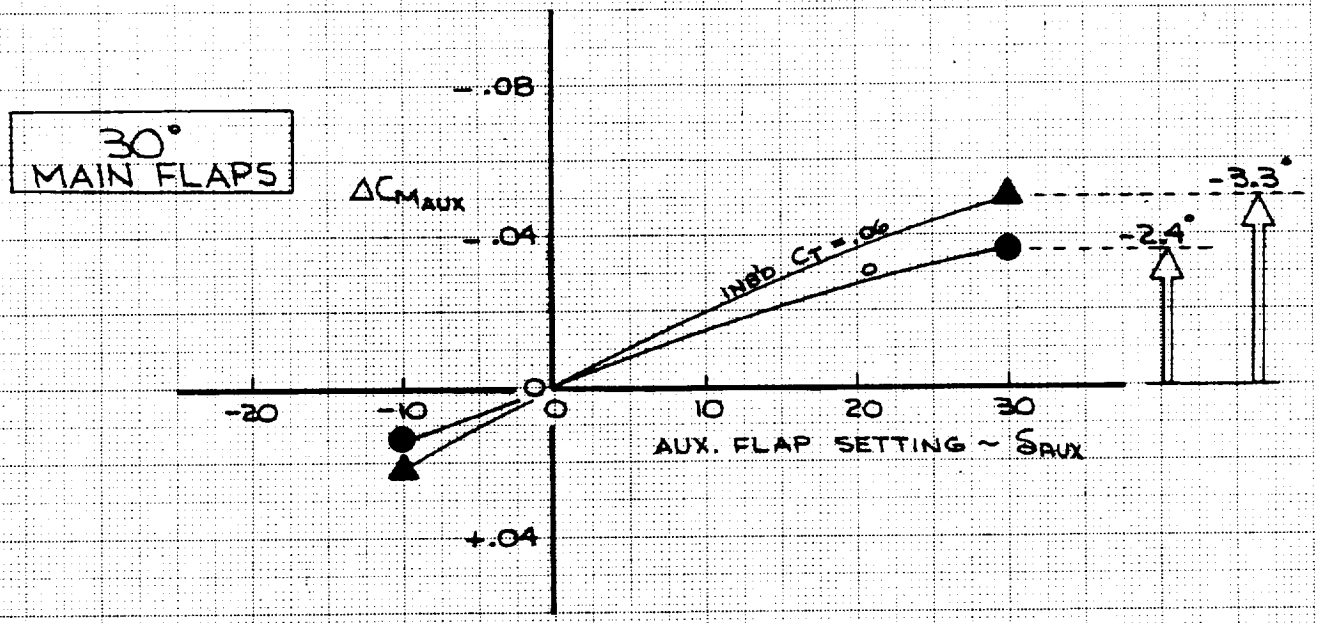
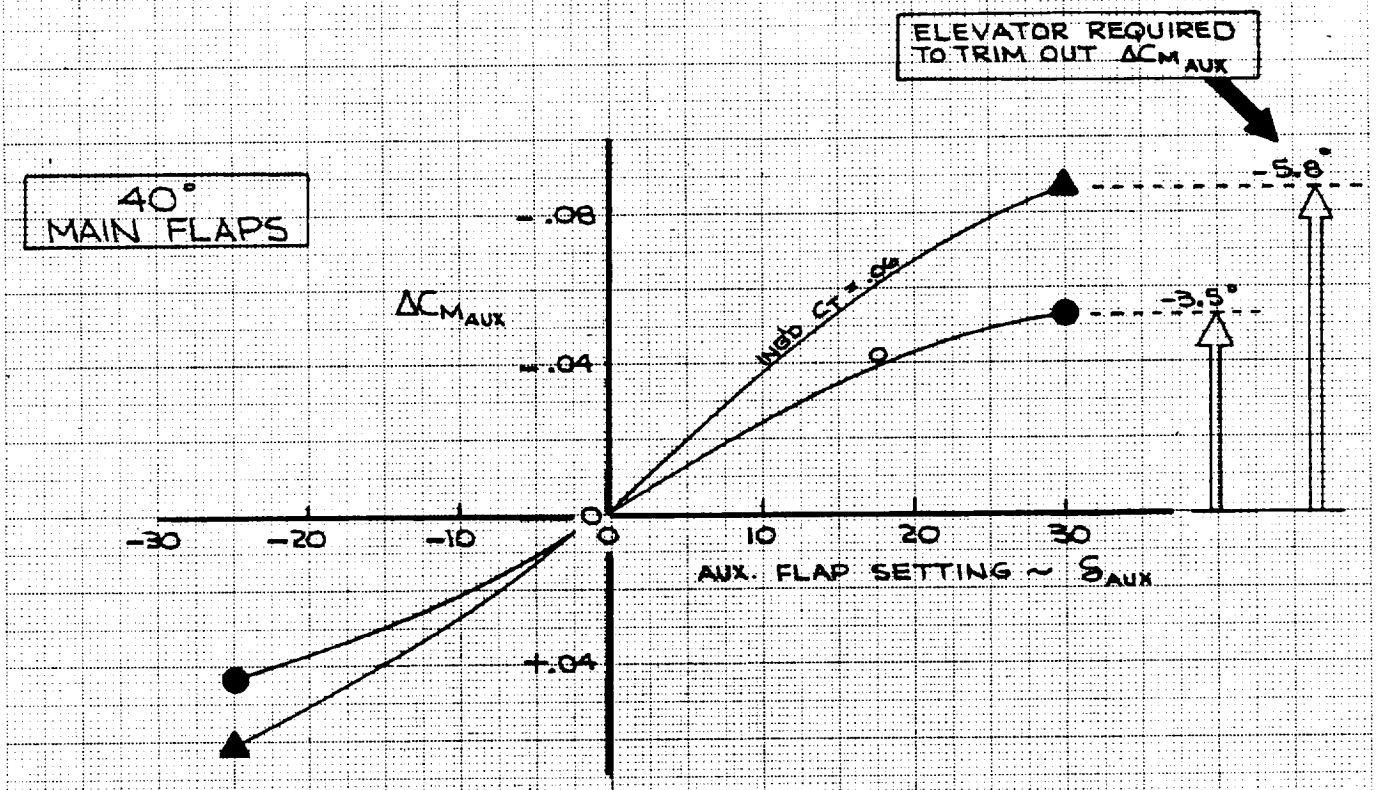
question. However, the ΔC_M's shown in Figure 20 are probably representative of what the actual airplane will undergo.

ELEVATOR REQUIREMENTS: Elevator requirements during free air approaches are within the 10° up-elevator simulation mode limit. The upper plot of Figure 21 shows the elevator required to trim out the pitching moment change due to auxiliary flap deflection. At 40° main flap with nominal inboard thrust, about 6° up-elevator is required with full-down auxiliary flap. However, elevator requirements in the simulation mode may pose a problem during landings when ground effects are encountered. Previous 367-80 wind tunnel and flight data show that a nose-down pitching moment change occurs in ground proximity and that this moment change becomes more nose-down with increasing free air lift coefficient. It may be seen from the lower plot of Figure 21 that trimming out the ΔC_M due to ground effect requires from 3° to 9° of up-elevator. Thus, it is possible to exceed the simulation mode elevator limit if both ground effect and down auxiliary flap are superimposed on each other. However, elevator electrical authority can be doubled by a relatively simple wiring change. The safety aspects of this increased authority will be studied and the change made if it is feasible and if flight test results confirm the foregoing data.



NOTES :

1. $\Delta C_{M_{AUX}}$ = PITCHING MOMENT INCREMENT DUE TO AUX. FLAP DEFLECTION AT CONSTANT ANGLE OF ATTACK = 4°
2. $C_{M_{\delta_e}} = +.015/_{DEG.}$ (367-80 VALUE)
3. DATA FROM AMES T-293 (40' x 80')



CALC	TAYLOR	7/67	REVISED	DATE	PITCHING MOMENT CHANGE DUE TO AUX. FLAP DEFLECTION WITH ELEVATOR REQUIREMENTS
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367-80
AMES
T-293
FIG. 20
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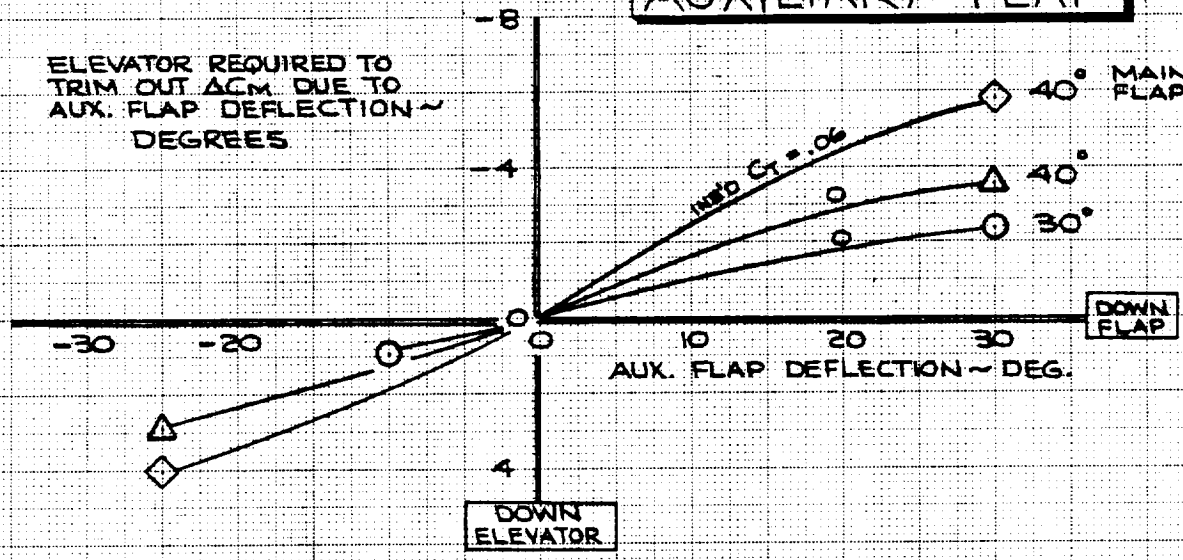
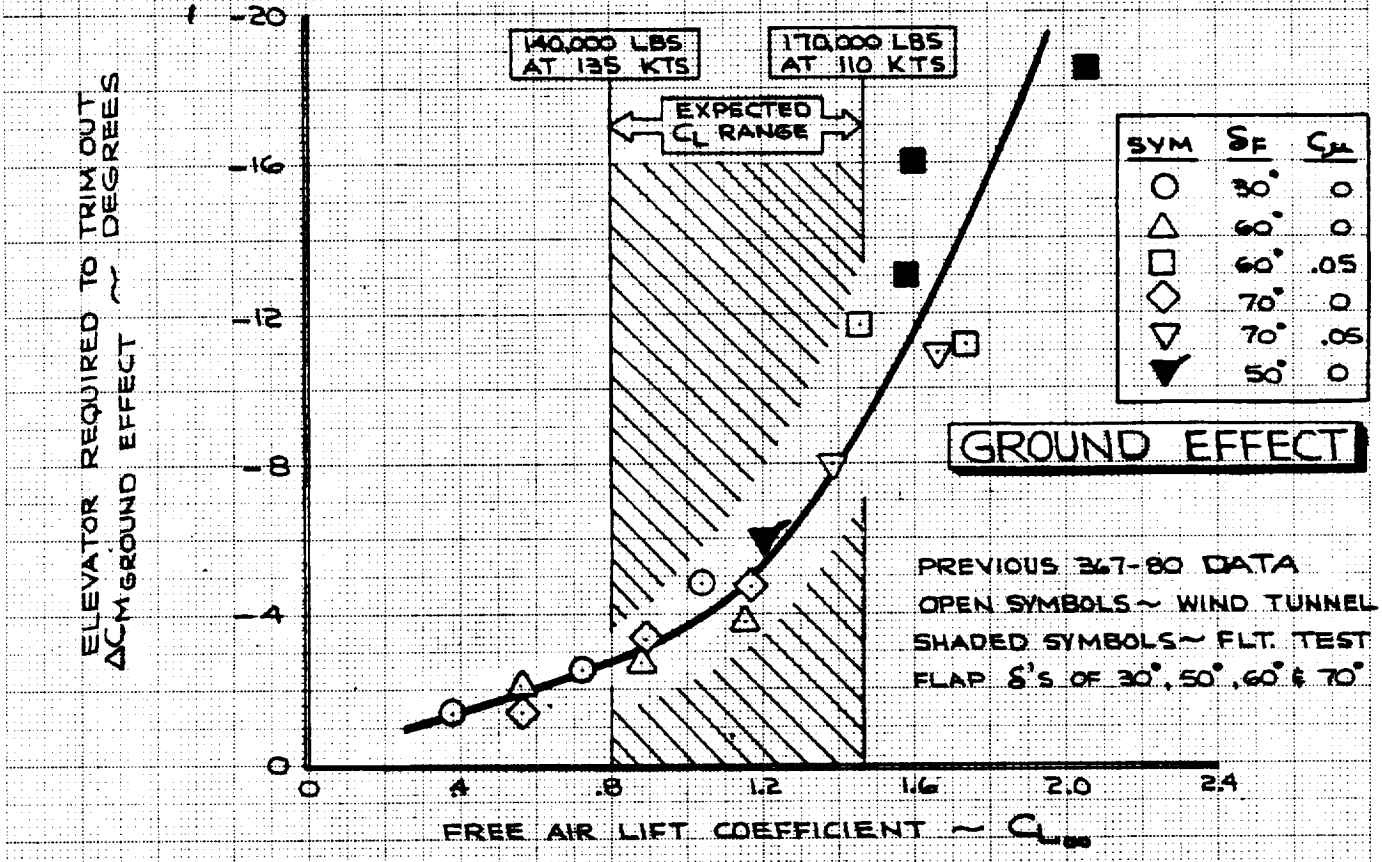
REF. : NASA AMES T-293

AUXILIARY FLAP



NOTE: $C_{m_{\delta_E}} = -.015/\text{DEG.}$



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ELEVATOR REQUIREMENTS FOR PITCHING MOMENT CHANGES DUE TO AUXILIARY FLAP DEFLECTION AND GROUND EFFECT

367-80

FIG. 21

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5.2 Airloads and Hinge-Moments

The DLC flap layout is shown in Figure 22 and the estimated flap loads and hinge-moments for the proposed 367-80 DLC system are shown in Figures 23 through 31. Loads and moments shown are for an auxiliary flap at 30° deflection with respect to a 30° main flap. Presentation of the loads and hinge-moments is made in the form of "carpet plots" with inboard thrust coefficient and dynamic pressure as the variables. (Note: The thrust coefficients noted in this loads section are for single engine thrust.) Shown on the plots are the cutoff lines for maximum attainable thrust coefficient (JT3D-1 sea-level takeoff thrust) and dynamic pressure at 160 knots (maximum flap actuation speed). The flaps are to be designed to have full actuation capability at 160 knots and takeoff thrust with both hydraulic systems operating. Also noted on the plots is the thrust coefficient required for level flight at 170,000 lbs gross weight, which represents a high weight condition, with 30° main flap (auxiliary flap faired).

The load and moment estimations were based on data from the first Ames wind tunnel test (T-280). The test data appeared in the form of sectional lift and drag coefficients at three spanwise stations. Only the sectional coefficients at the middle station (η = .43) were used to construct what was felt to be representative spanwise loading curves of normal and axial forces for the proposed auxiliary and main flaps as shown in

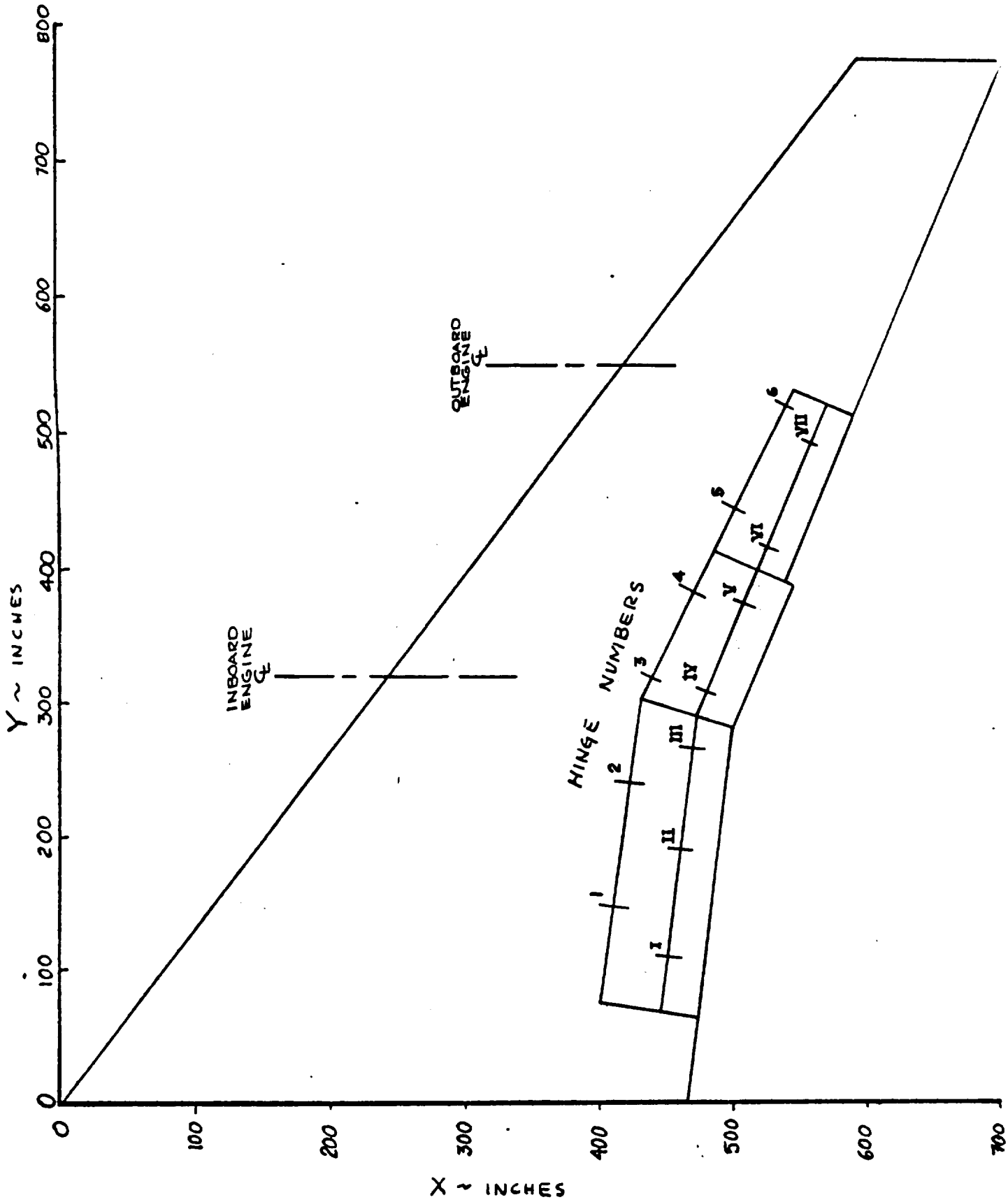
Figures 32 and 33 respectively. The sectional lift coefficients at the other two span stations (η = .30 and .56) appeared to be unduly low and were not used in the determination of the load distribution. (It is not explicitly known why the values were so low for these two stations, but it is felt that the location of their static pressure sources near gaps in the flap may have contributed to unrealistic pressure data.) Inboard engine thrust effects on the sectional coefficients as determined from T-280 were also included. The straight-line shape of the spanwise loading curves was assumed for simplicity in spanwise integration. The estimated loads and hinge-moments were calculated for $\alpha = 0^{\circ}$; however, the test data showed the sectional lift coefficients to be invariant with angle of attack. Also, test data was available only for a 30° main flap setting and auxiliary flap settings of 15° and 30°. The auxiliary flap loads and hinge-moments were calculated for 30° auxiliary flap as the test data showed no variance in sectional lift between 15° and 30° auxiliary flap. Figure 34 shows the sign convention used in the computations.

5.3 Hydraulic Power Analysis

5.3.1 Design Ground Rules

The following design ground rules were adopted for the DLC flap actuation system:

- Actuators must be flight qualified primary control surface actuators. No actuator development or proof test is required.



ENGR. J. DENGMORE 8/4/67	REVISED	DATE	367-80 DLC FLAP SYSTEM	
CHECK				D6-19580
APR				PAGE 49
APR			THE BOEING COMPANY RENTON, WASHINGTON	FIGURE 22

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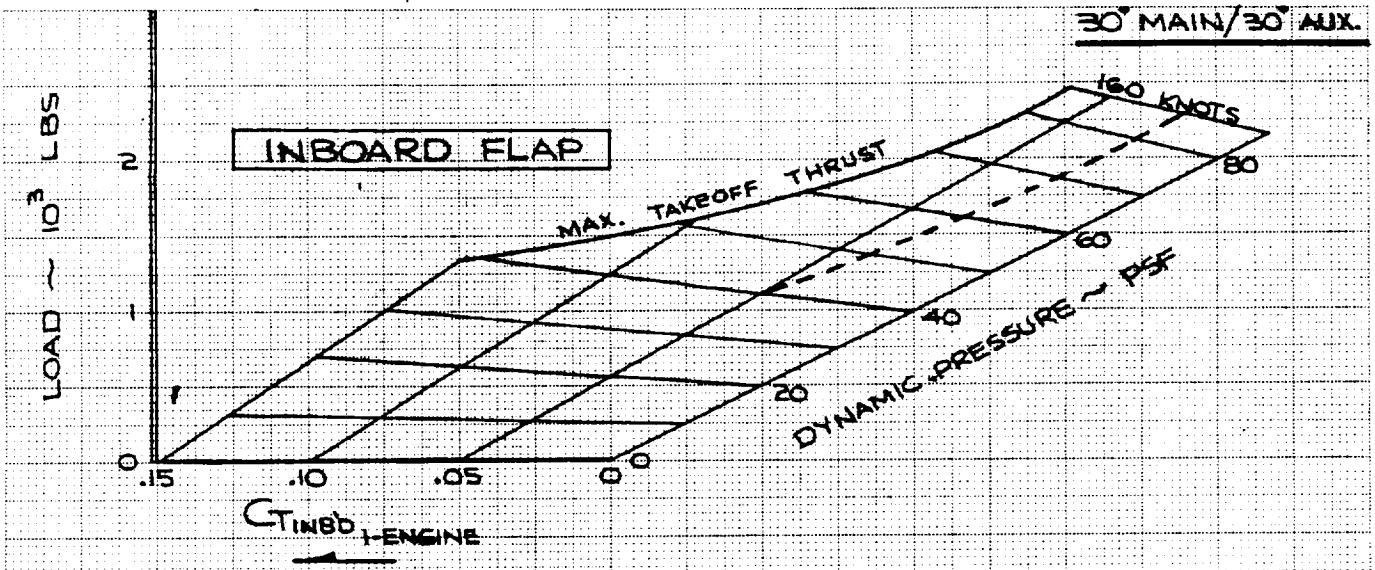
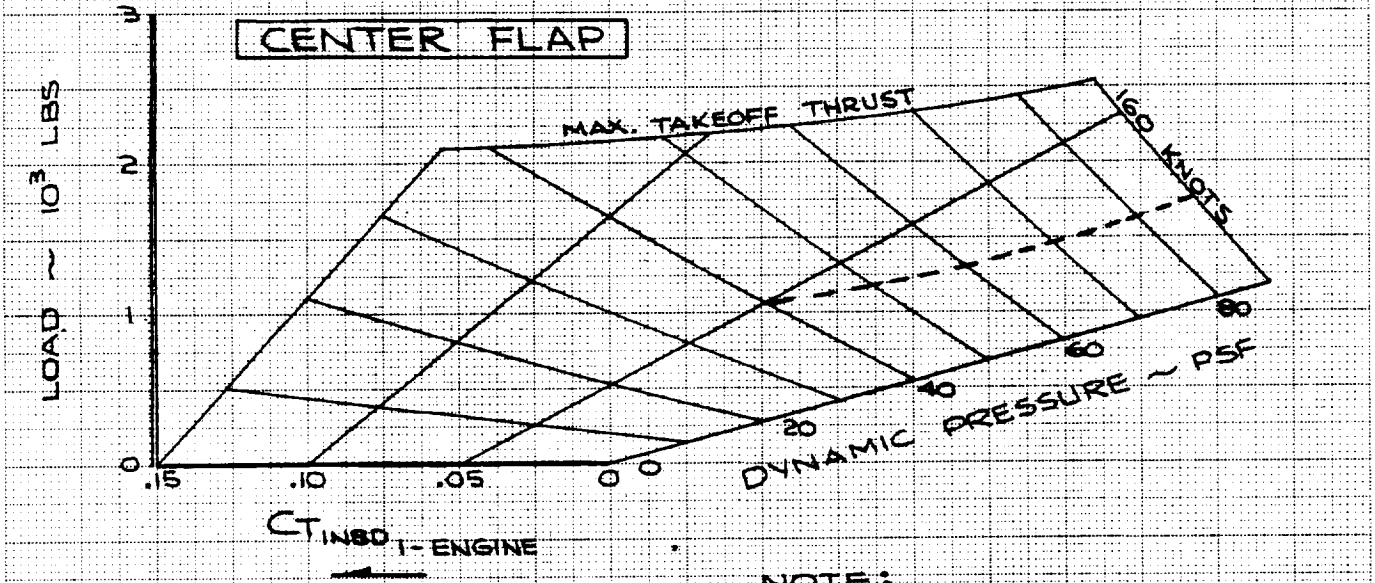
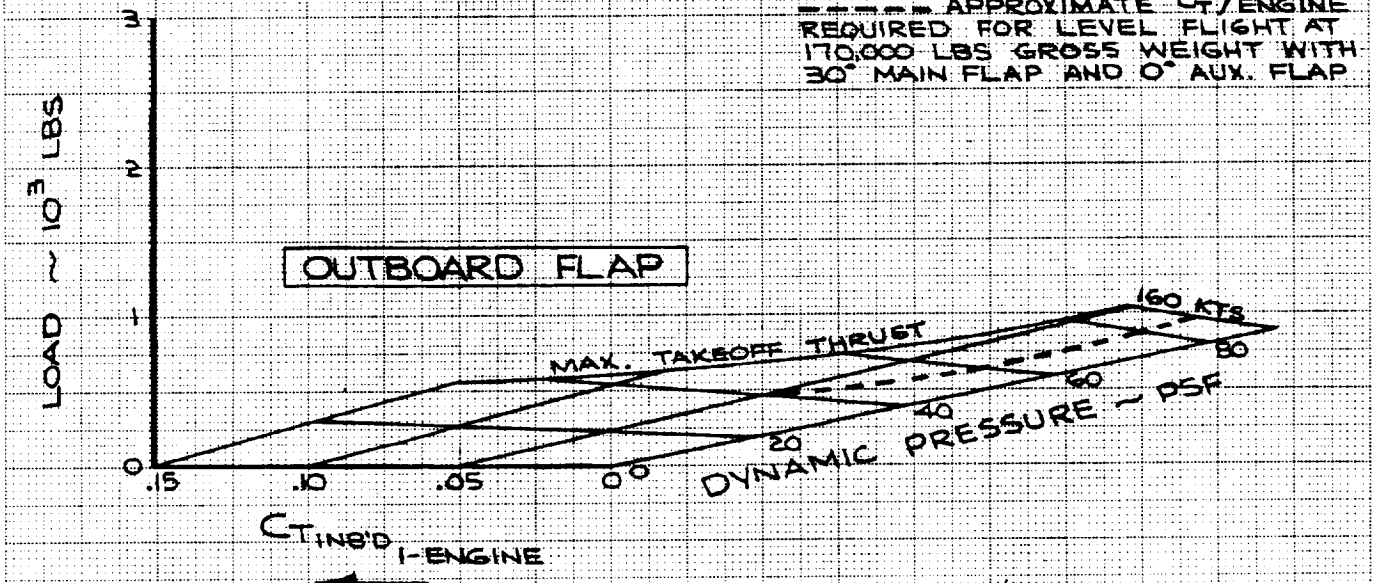
30° MAIN/30° AUX.





NOTE:
------ APPROXIMATE C_T/ENGINE REQUIRED FOR LEVEL FLIGHT AT 170,000 LBS GROSS WEIGHT WITH 30° MAIN FLAP AND 0° AUX. FLAP



CALC	DENSMORE	8/67	REVISED	DATE	AUXILIARY FLAP NORMAL LOADS	367-80 DLC
CHECK			TAYLOR	8/67		FIG. 23
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APR					THE BOEING COMPANY	PAGE 50 D6-19580

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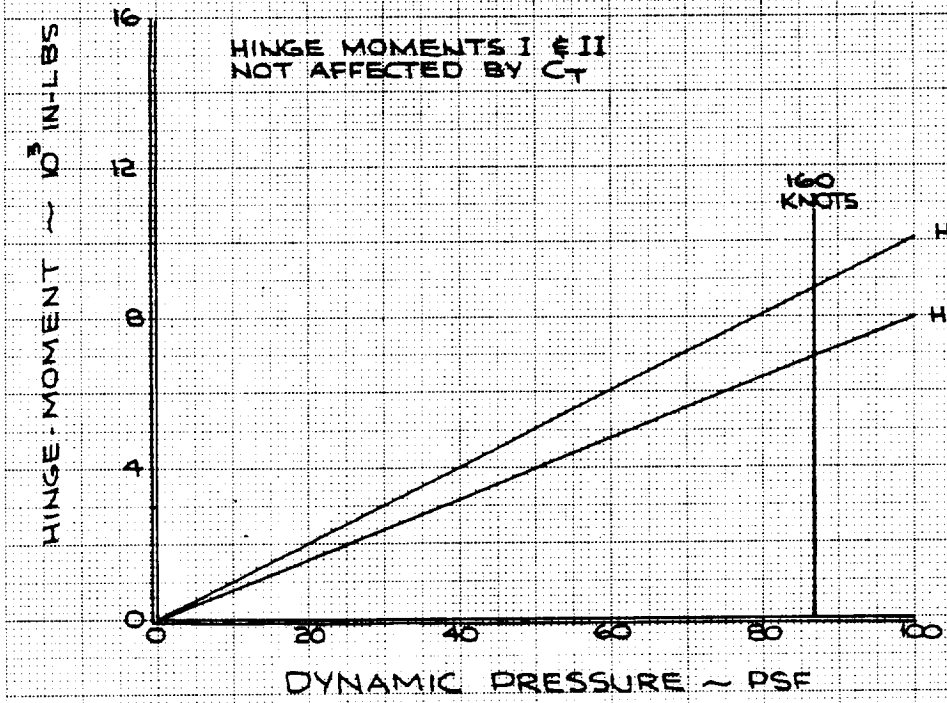
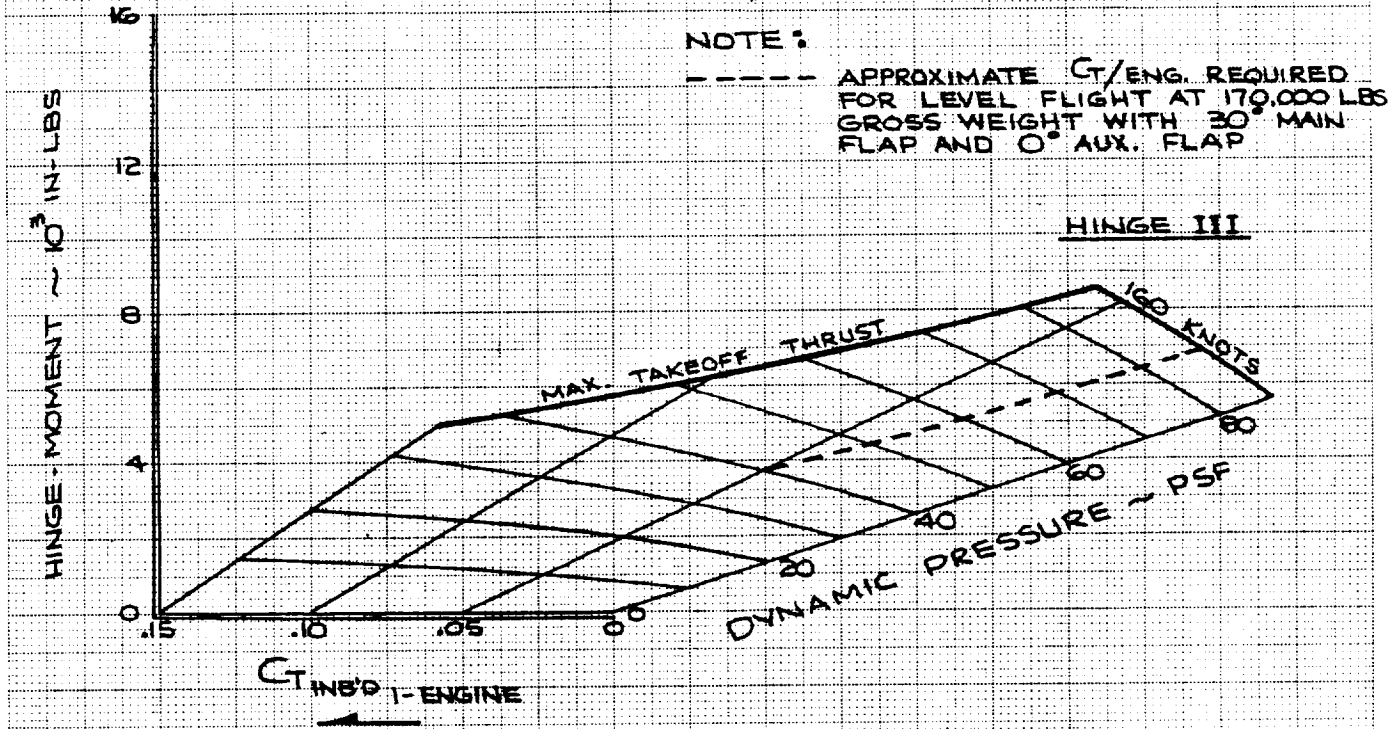
INBOARD FLAP

HINGES I, II & III

30° MAIN/30° AUX.





CALC	DENSMORE	8/67	REVISED	DATE	AUXILIARY FLAP HINGE-MOMENTS INBOARD FLAP
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					THE BOEING COMPANY

367-80 DLC

FIG. 24

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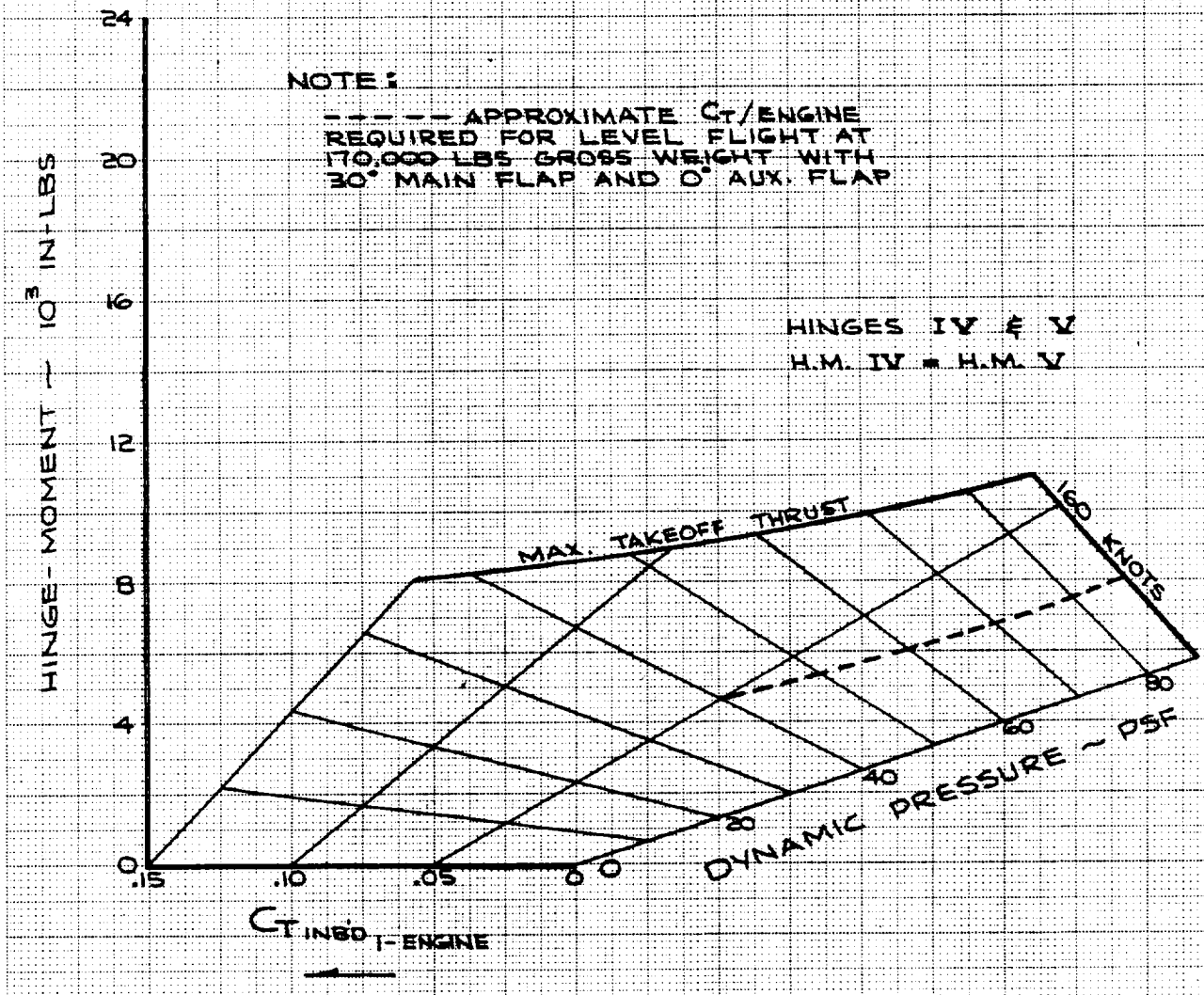
CENTER FLAP

HINGES IV & V

30° MAIN/30° AUX.



CALC	DENSMORE	8/67	REVISED	DATE	AUXILIARY FLAP HINGE-MOMENTS CENTER FLAP	367-80 DLC FIG. 25
CHECK			TAYLOR	8/67		
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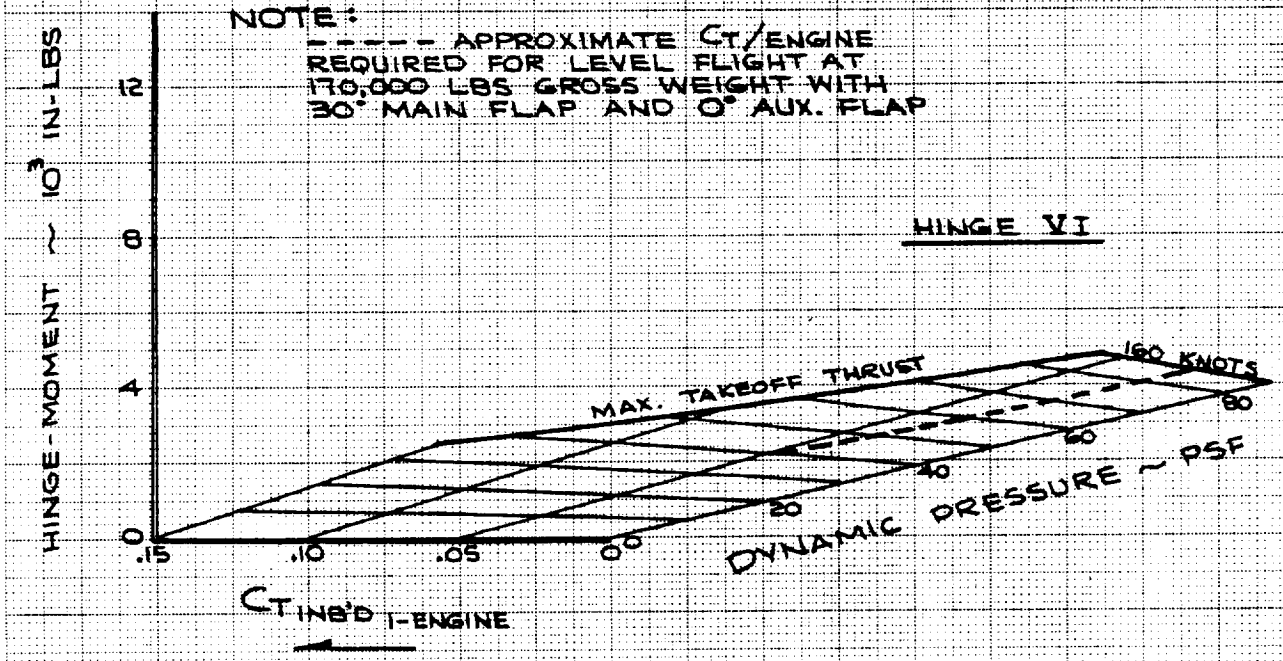
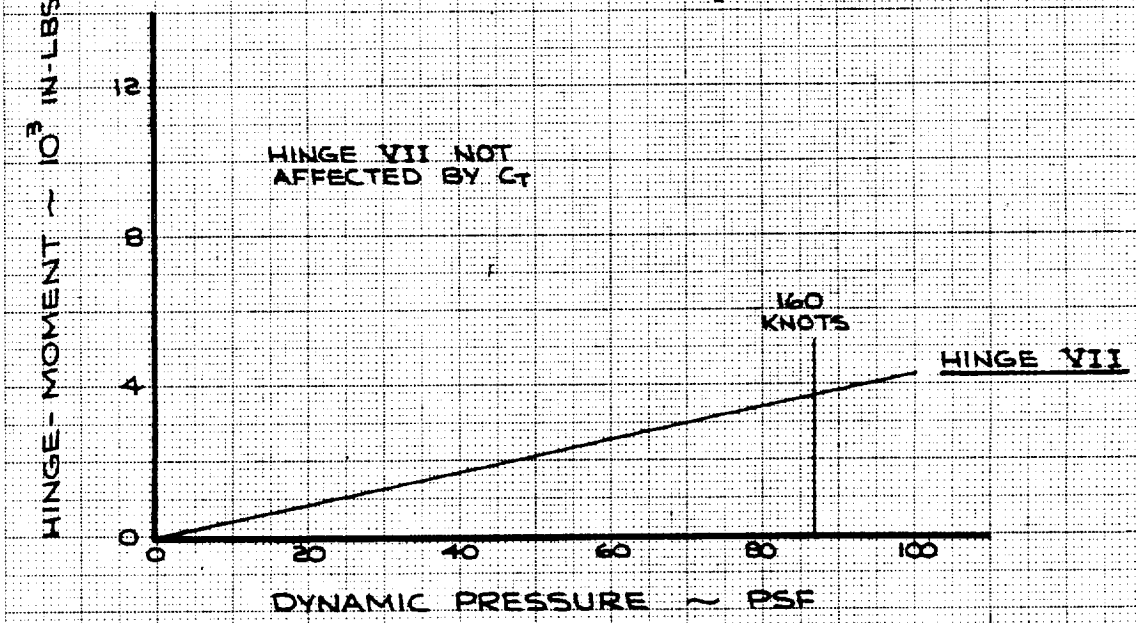
OUTBOARD FLAP

HINGES VI & VII

30° MAIN / 30° AUX.





CALC	DENSMORE	8/67	REVISED	DATE	AUXILIARY FLAP HINGE-MOMENTS OUTBOARD FLAP THE BOEING COMPANY
CHECK			TAYLOR	8/67	
APR					
APR					

367-80 DLC

FIG. 26

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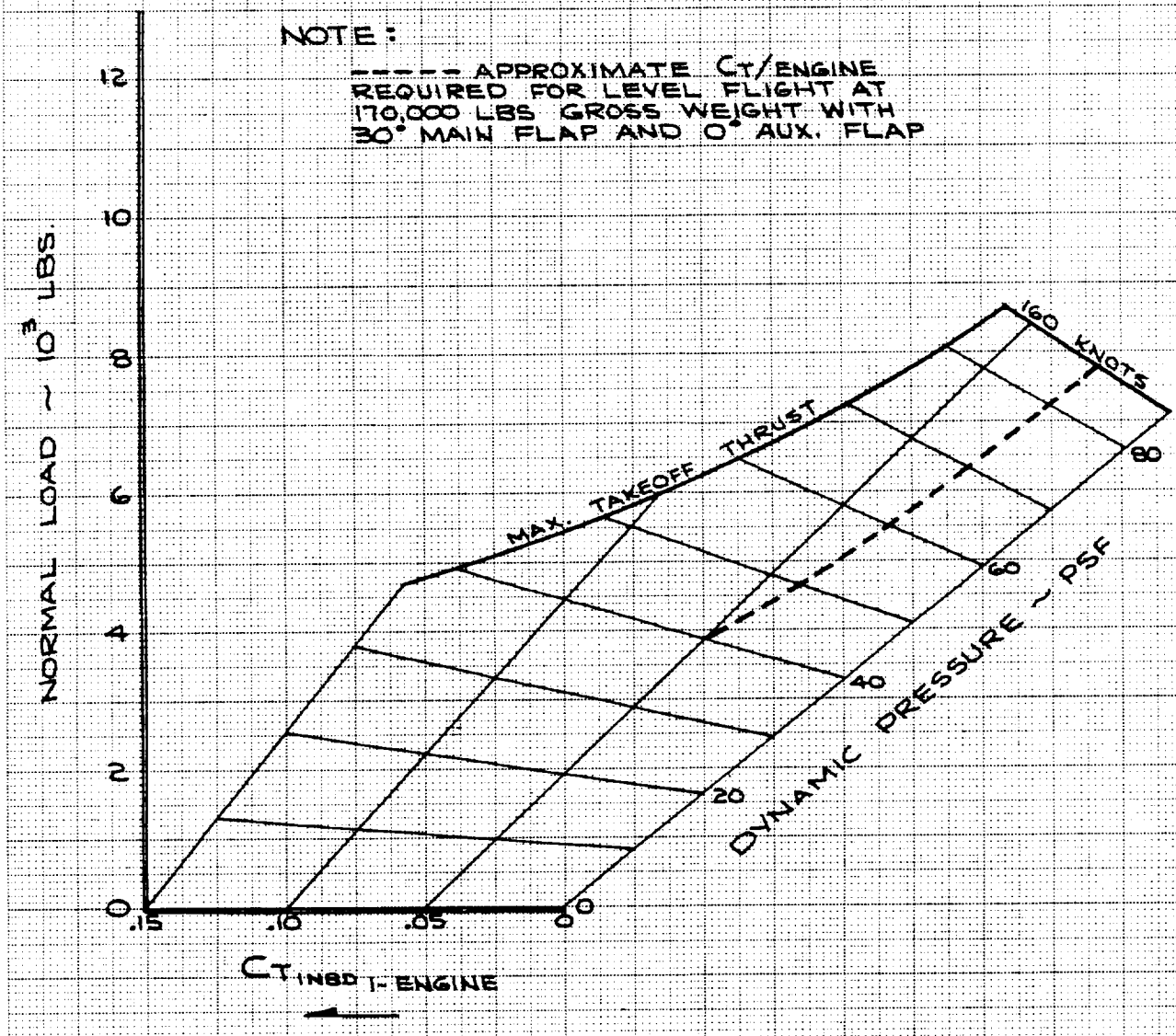
INBOARD MAIN FLAP

30° MAIN/30° AUX.

NOTE:

----- APPROXIMATE C_T/ENGINE REQUIRED FOR LEVEL FLIGHT AT 170,000 LBS GROSS WEIGHT WITH 30° MAIN FLAP AND 0° AUX. FLAP



CALC	TAYLOR	8/67	REVISED	DATE	MAIN FLAP NORMAL LOAD INBOARD	367-80 DLC FIG. 27
CHECK						
APR						
APR					THE BOEING COMPANY	PAGE 54 D6-19580

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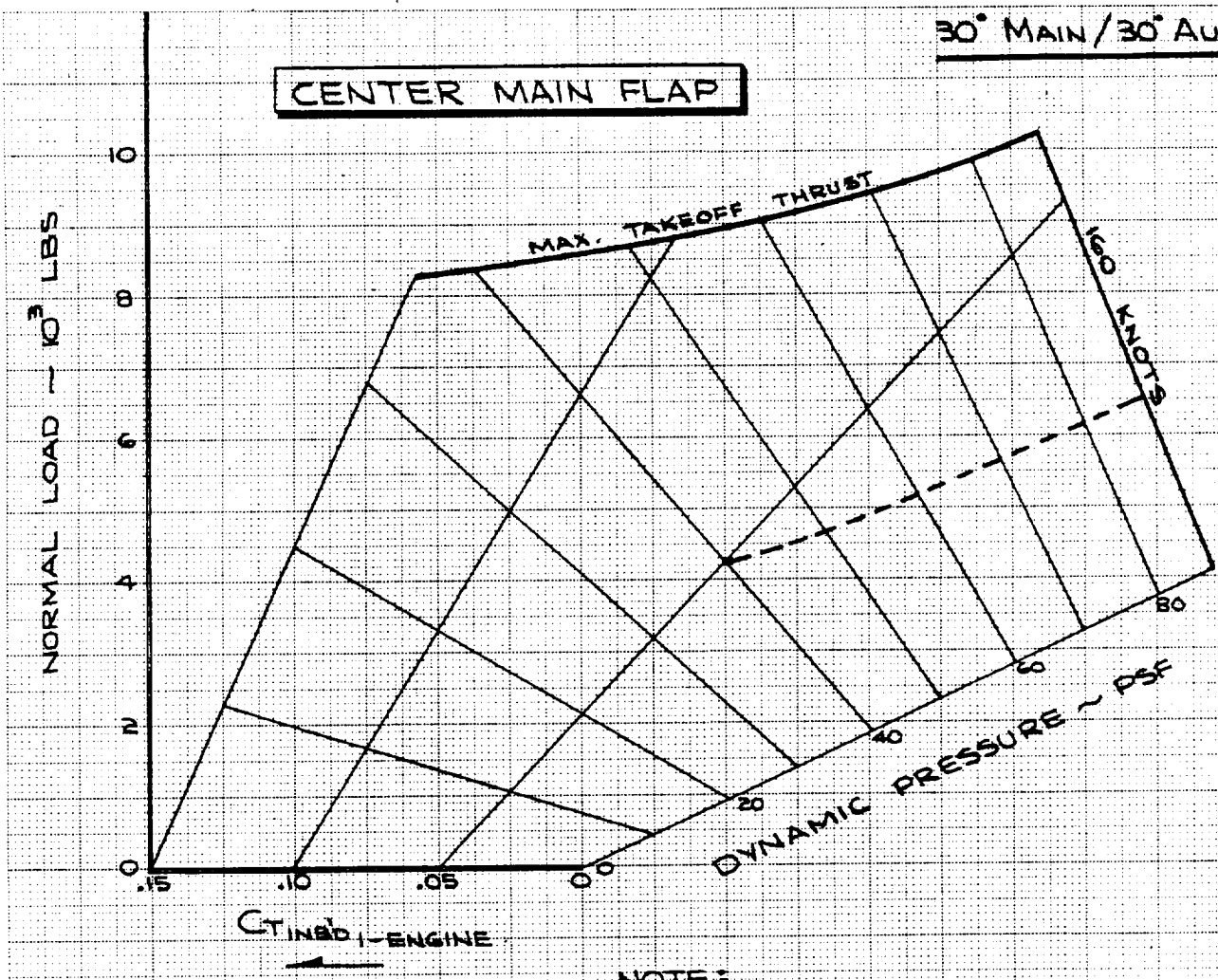
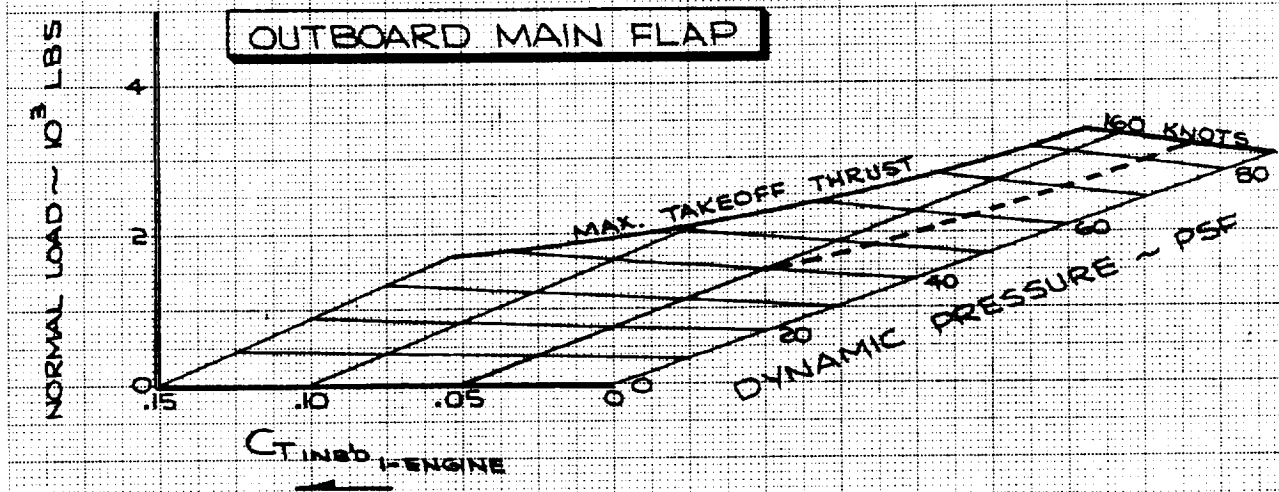
30° MAIN / 30° AUX.

CENTER MAIN FLAP



NOTE:
------ APPROXIMATE C_T/ENGINE REQUIRED FOR LEVEL FLIGHT AT 170,000 LBS GROSS WEIGHT WITH 30° MAIN FLAP AND 0° AUX. FLAP

OUTBOARD MAIN FLAP



CALC	DENSMORE	8/67	REVISED	DATE	MAIN FLAP NORMAL LOADS CENTER AND OUTBOARD
CHECK			TAYLOR	8/67	
APR					
APR					
					THE BOEING COMPANY

367-80 DLC
FIG. 28
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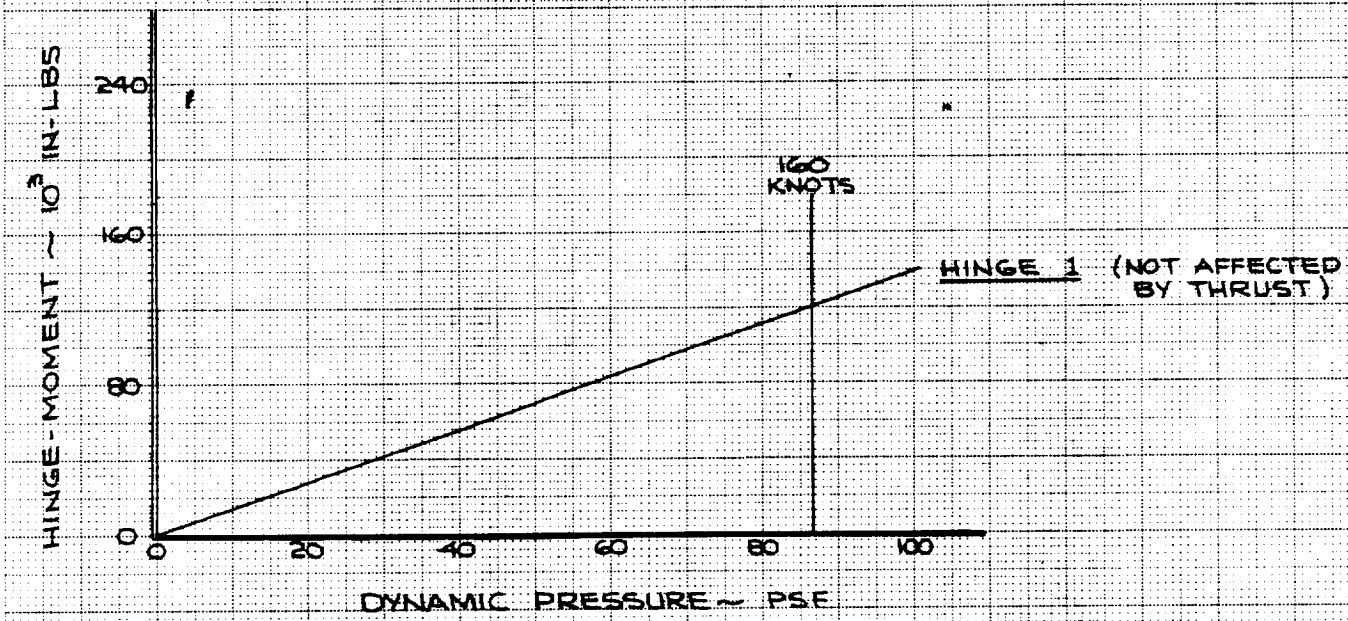
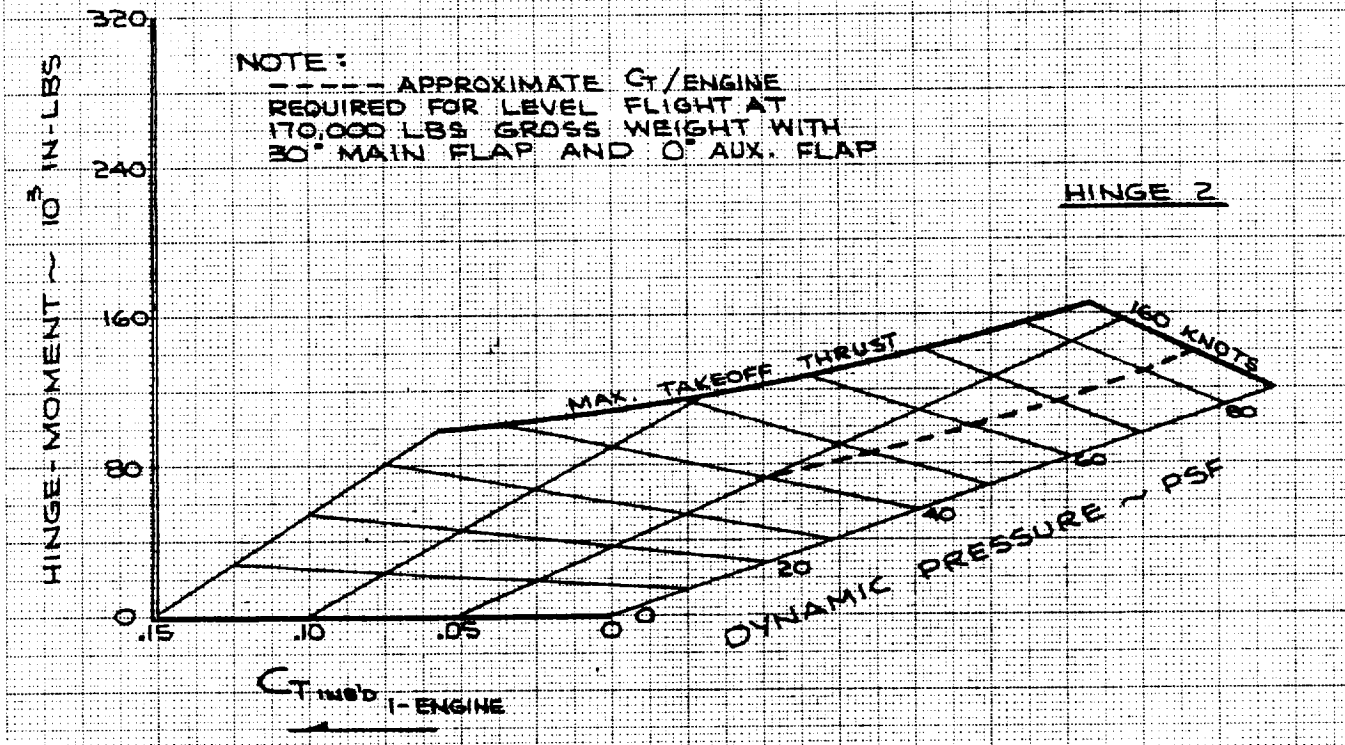
INBOARD MAIN FLAP

30° MAIN / 30° AUX.

HINGES 1 AND 2





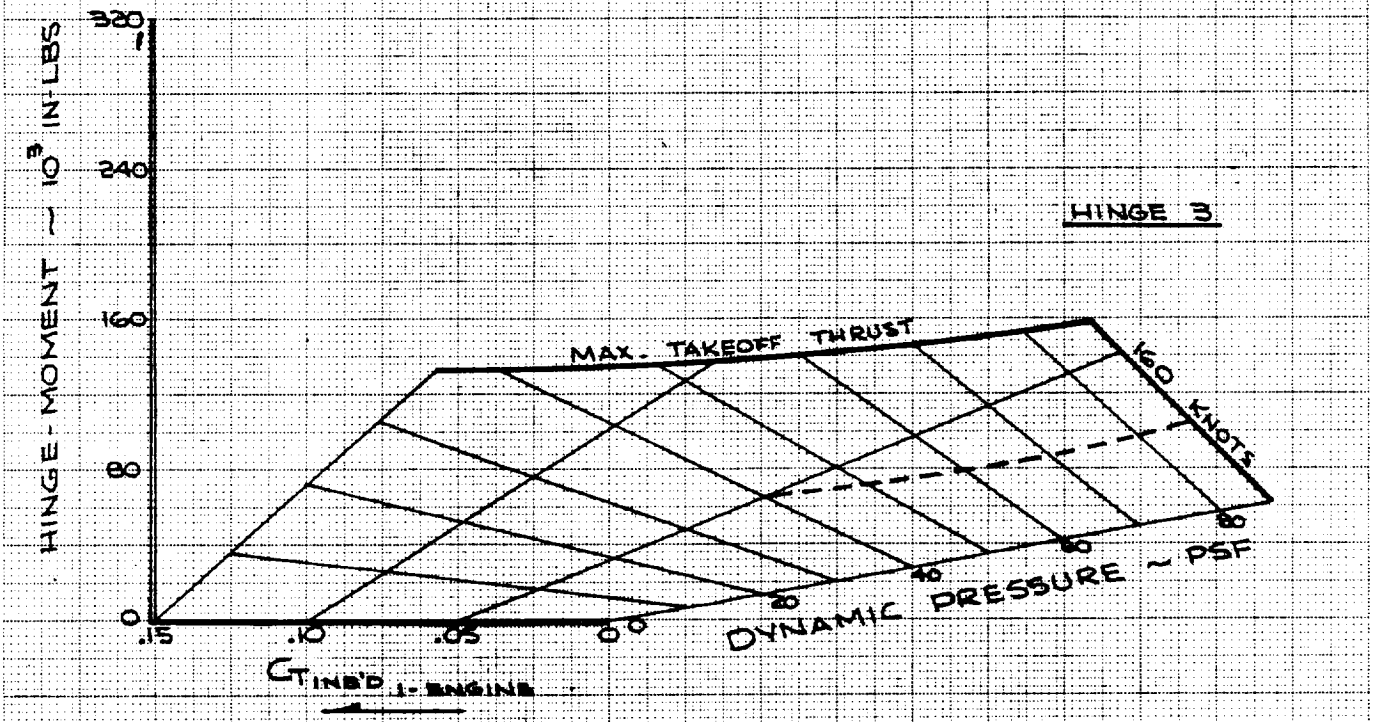
CALC	DENSMORE	8/67	REVISED	DATE	MAIN FLAP HINGE-MOMENTS INBOARD FLAP THE BOEING COMPANY
CHECK			TAYLOR	8/67	367-80 DLC FIG. 29 PAGE 56 D6-19580
APR					
APR					

TD 461.D

CENTER MAIN FLAP

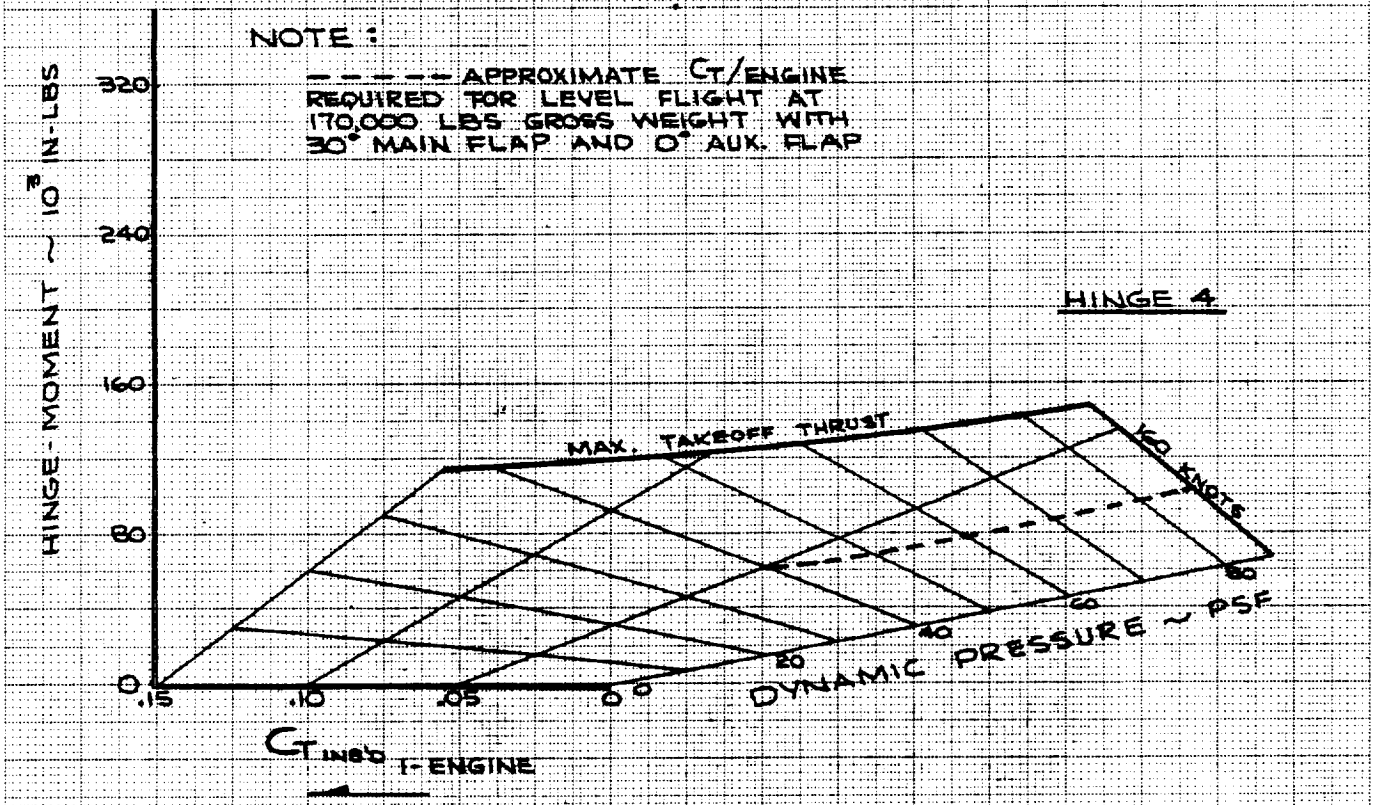
30° MAIN / 30° AUX.

HINGES 3 AND 4



NOTE:

– – – – – APPROXIMATE C_T/ENGINE REQUIRED FOR LEVEL FLIGHT AT 170,000 LBS GROSS WEIGHT WITH 30° MAIN FLAP AND 0° AUX. FLAP



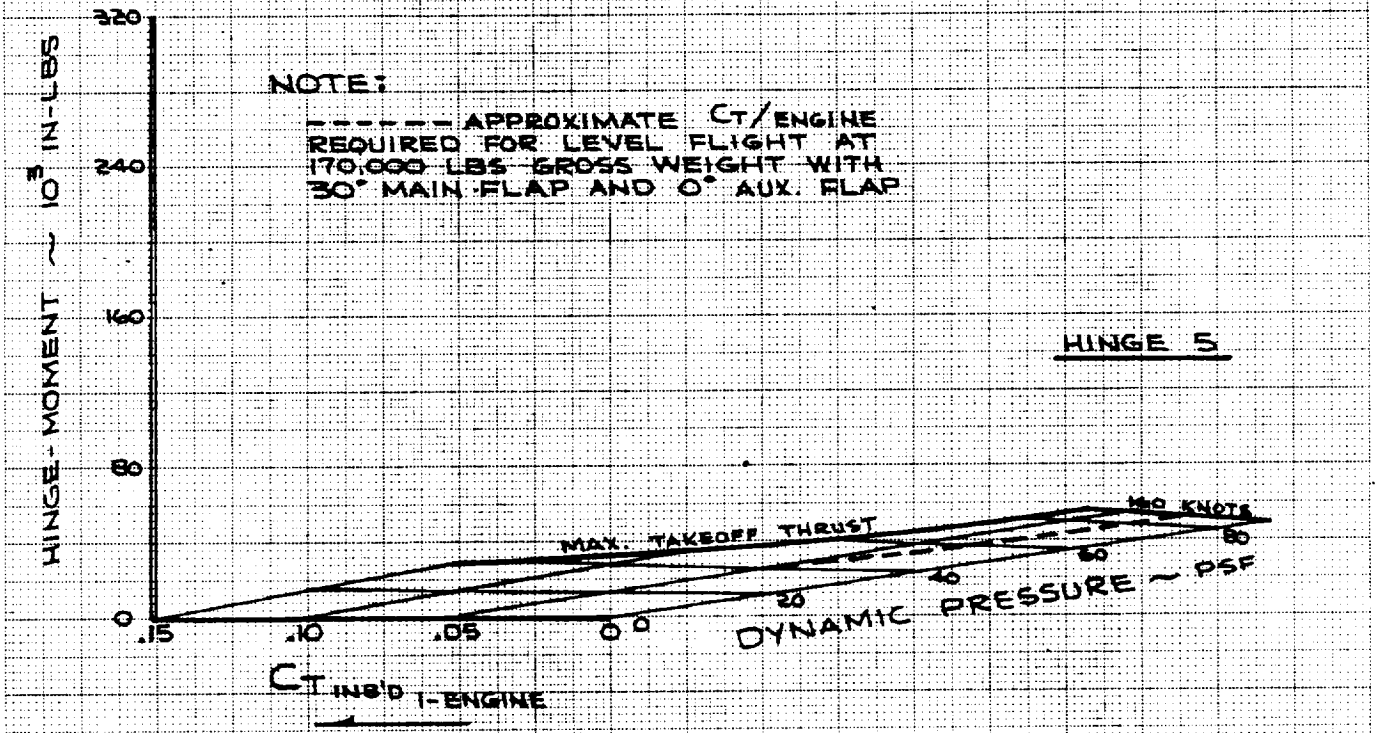
CALC	DENSMORE	8/67	REVISED	DATE	MAIN FLAP HINGE-MOMENTS CENTER FLAP THE BOEING COMPANY
CHECK			TAYLOR	8/67	367-80 DLC FIG. 30 PAGE 57 D6-19580
APR					
APR					

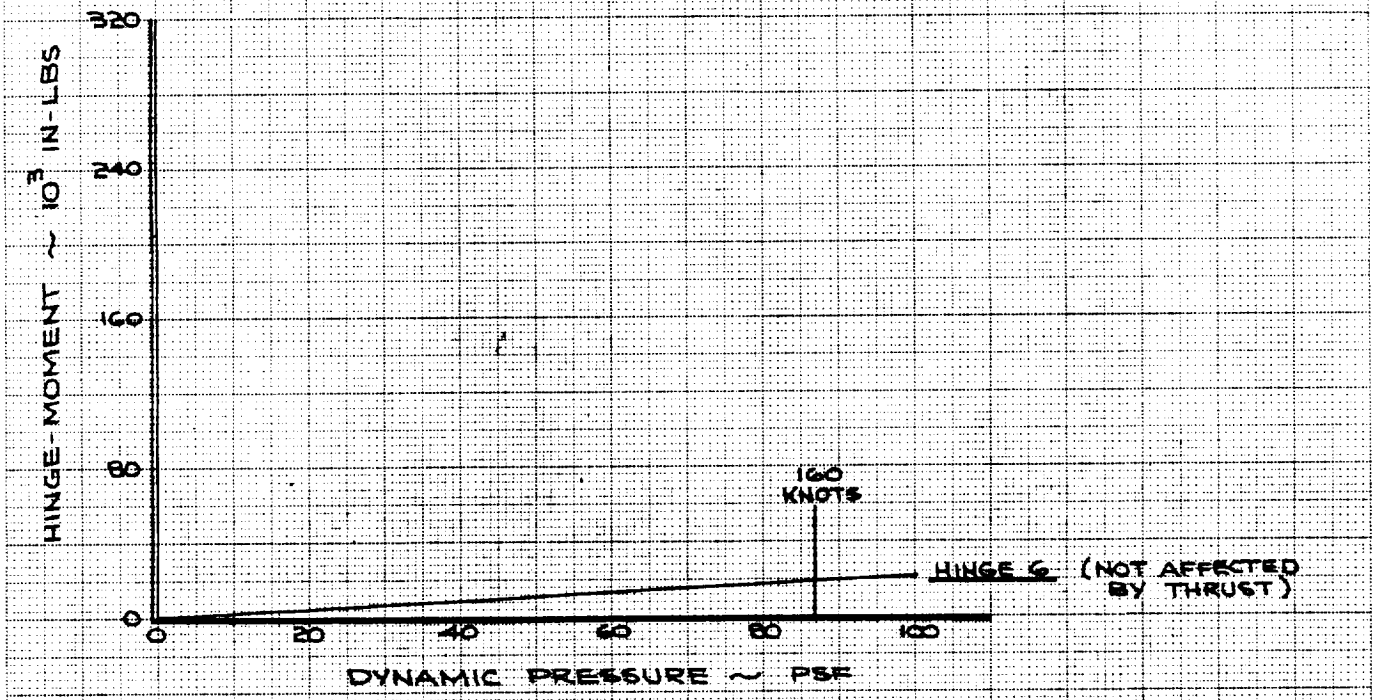
TD 461 D

OUTBOARD MAIN FLAP

30° MAIN/30° AUX.

HINGES 5 AND 6





CALC	DENSMORE	8/27	REVISED	DATE	MAIN FLAP HINGE-MOMENTS OUTBOARD FLAP
CHECK			TAYLOR	8/27	
APR					
APR					
					THE BOEING COMPANY

367-80 DLC

FIG. 31

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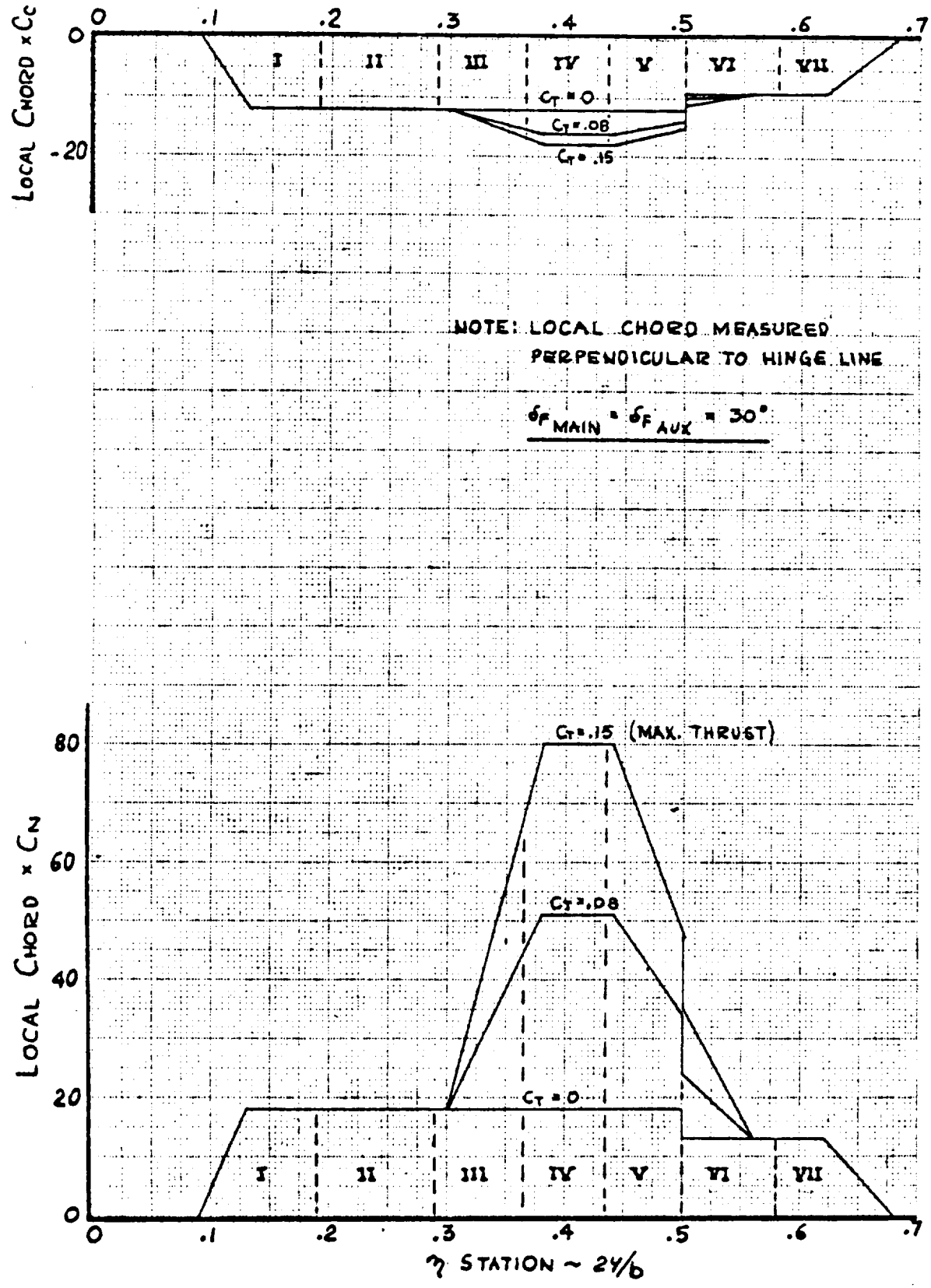
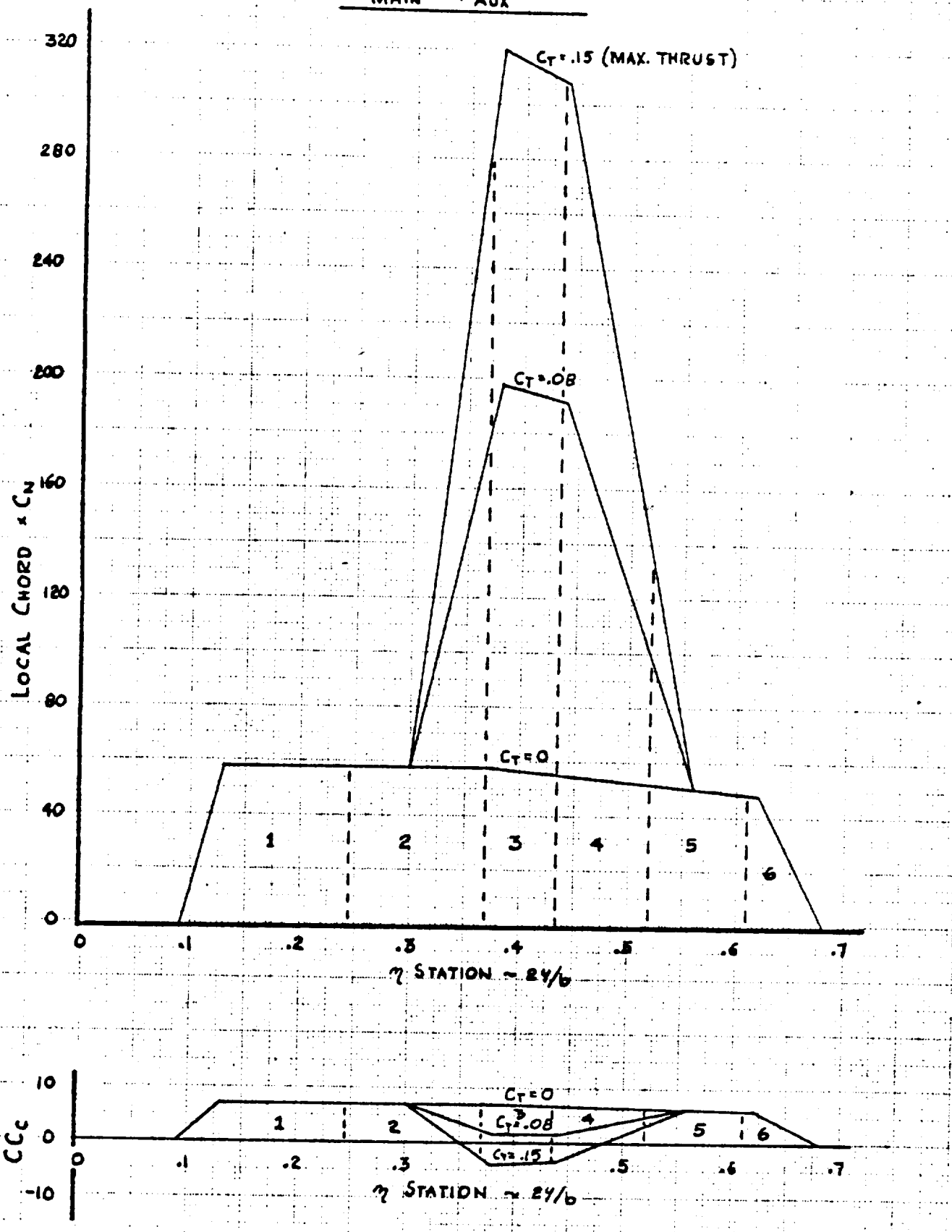


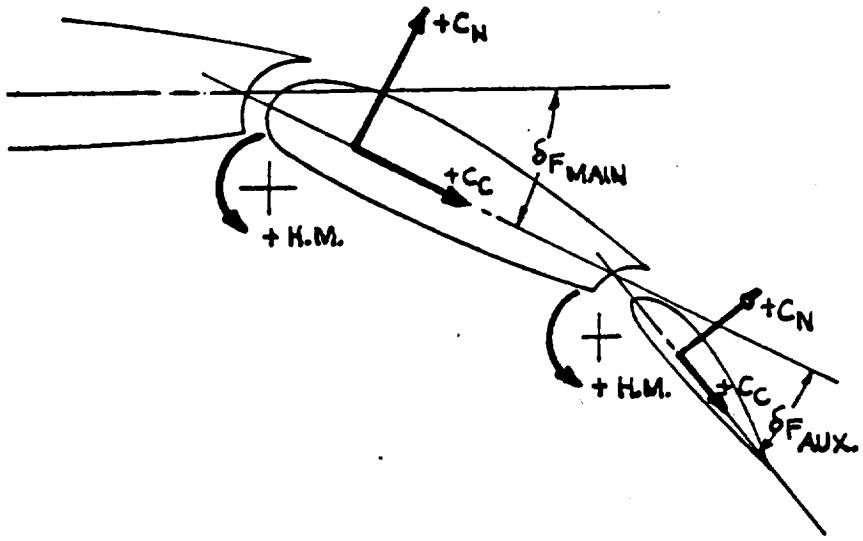
CALC	J. DENSMORE 7/7/67	REVISED	DATE	LOAD DISTRIBUTION AUXILIARY FLAPS -80 DLC FLAP STUDY	FIG. 32
CHECK					
APPD					
APPD				THE BOEING COMPANY	PAGE 59 D6-19580

NOTE: CHORD MEASURED PERPENDICULAR TO HINGE LINE

$\delta_{F_{MAIN}} = \delta_{F_{AUX}} = 30°$



CALC	J. DENSMORE	8/1/67	REVISED	DATE	MAIN FLAP LOAD DISTRIBUTION	
CHECK					-80 DLC FLAP STUDY	FIG. 33
APR						
APR					THE BOEING COMPANY	PAGE 60 D6-19580



SIGN CONVENTIONS AND
FLAP DEFLECTION MEASUREMENT

$$C_N = C_l \cos\delta + C_d \sin\delta$$
$$C_C = -C_l \sin\delta + C_d \cos\delta$$

WHERE $\delta_M = \alpha_W + \delta_{F_{MAIN}}$ (MAIN FLAP)

$\delta_A = \alpha_W + \delta_{F_{MAIN}} + \delta_{F_{AUX}}$ (AUX. FLAP)

ENGR.	J. DENSMORE	7/26/67	REVISED	DATE	SIGN CONVENTION FOR FLAP LOADS	FIG. 34
CHECK						
APR						
APR					THE BOEING COMPANY RENTON, WASHINGTON	D6-19580 PAGE 61

TO 1017-R6

6-7000

- Auxiliary flap actuation rate must be 20°/sec. Higher rates are desirable if possible considering other requirements.
- Total system hydraulic flow requirement shall be within capacity of 367-80 system including all other flight system demands excluding landing gear or main flap actuation. This requirement shall be met with all engines at 58% rpm.
- Total angular travel of auxiliary flaps is 40° minimum.
- No single failure shall cause a steady state asymmetrical auxiliary flap deflection.
- In the event of an electrical signal failure or simulation disconnect, the auxiliary flap actuators shall return to neutral position at a controlled rate.
- Single hydraulic system failure shall not prevent auxiliary flaps from being held at neutral position at approach speed. (Auxiliary flap up-float at higher speeds is allowable.)
- Main flaps shall be operable in flight.

5.3.2 Actuator

A preliminary survey of commercially available flight control actuators narrowed the choice to two which met the requirements and with which there is Boeing Company experience. These were the B-52 elevator actuator

designed for the LAMS program (Boeing Wichita) and the modified 727 elevator actuator used as the 367-80 elevator actuator. The analysis herein presented was initially performed assuming use of the B-52 elevator actuator. Subsequently a price comparison from vendor quotations eliminated this actuator from consideration and modifications to the analysis and design have been made as required to accommodate use of the 367-80 elevator actuator, Dwg. No. 10-60362-1.

5.3.2.1 Surface Authority

Actuator stroke is 3.30 inches which requires a surface arm of 4.82 inches to provide the total surface deflection of 40°.

5.3.2.2 Actuator Centering

The selected actuator design is such that during electrical mode operation, the actuator output position is reflected at the mechanical input linkage. To allow for the required input linkage motion and provide mechanical centering of the actuator upon loss of electrical signal, the actuator mechanical input is grounded to the main flap structure through a spring cartridge.

The centering rate of the actuator on loss of electrical signal is controlled by a solenoid

valve which allows free return flow when energized and introduces a restrictor in the return line when de-energized. Centering rate will be thus limited to approximately 4°/sec. This design is an expediency to provide the desired centering characteristics with the selected actuator and would not be recommended for a production system.

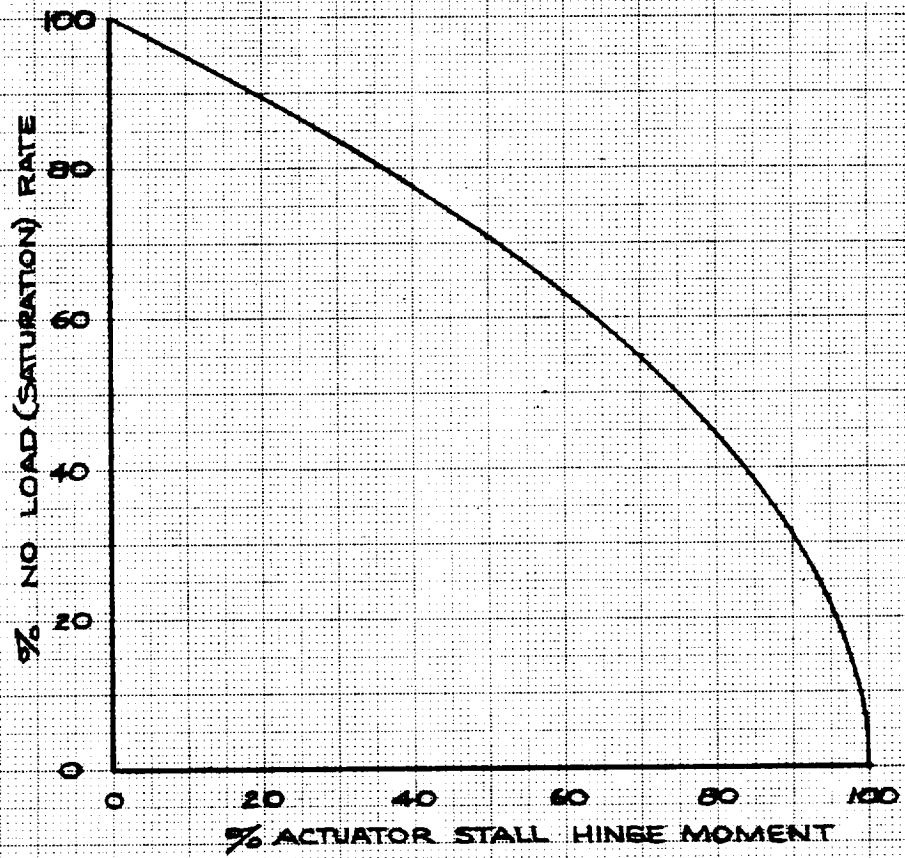
5.3.2.3 Hinge Moment Capability

The auxiliary flap hinge moments are discussed in the Aerodynamics Section (5.1). Hinge moments are shown in Table 2 for two flight conditions, maximum thrust at 160 knots, the simulation limit speed, and a representative test condition of 130 knots with thrust for level flight. It is seen that with both hydraulic systems operating the available actuator hinge moment is adequate to operate the auxiliary flaps at their most severe operating condition. With a system failure sufficient hinge moment capability exists to hold the auxiliary flaps at test conditions. Considering the conservatism used in treating the limited aerodyanamic data available, it is felt that this satisfies the ground rule requiring neutral auxiliary flap

deflection at approach speeds and the design objective of preventing abrupt lift loss near the ground due to single failures.

5.3.2.4 Actuation Rate

The saturation rate of the selected actuator in the electrical mode is 1.96 in/sec or 23.8 deg/sec with the 4.82 in. surface arm. Using the relationship between actuator hinge moment and rate shown in Figure 35, gives a maximum rate of 17.2 deg/sec at test conditions and approximately 11 deg/sec at simulation limit speed for the inboard auxiliary flap. This is somewhat short of the desired 20 deg/sec rate, but considering the available hydraulic supply, system cost, etc. seems to be the best solution. A further discussion of alternatives is included in section 5.3.3.



CALC			REVISED	DATE	SATURATION RATE OF AUXILIARY FLAP ACTUATOR	367-80 DLC
CHECK						FIG. 35
APR						
APR					THE BOEING COMPANY	PAGE 66 D6-19580

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TABLE 2

Flap Segment	Auxiliary Flap Actuation Hinge Moment			
	V_e = 160 KT Maximum Thrust		V_e = 130 KT Thrust for Level Flight	
	Aero Hinge Moment (In. Lbs.)	$\Delta P_{req'd}$ (1)(2) 2 Systems (PSI)	Aero Hinge Moment (In. Lbs.)	$\Delta P_{req'd}$ (1)(2) 1 System (PSI)
Inboard	24,300	2,370	15,200	2,960
Center	22,000	2,140	12,000	2,340
Outboard	8,500	830	5,400	1,050

(1) $\Delta P_{req'd}$ is the pressure differential required across the auxiliary flap actuator to produce the tabulated hinge moment.

(2) Actuator stall hinge moment at 3,000 PSI system pressure is 15,400 in-lb per system.

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5.3.3 Hydraulic System Modifications

The 367-80 airplane has two independent hydraulic systems, designated the left-hand and right-hand systems. The engine-driven pumps on engines #1 and #2 supply the L.H. hydraulic system and those on engines #3 and #4 the R.H. system. The pumps on the outboard engines have approximately 36% of the flow capacity of those on the inboard engines.

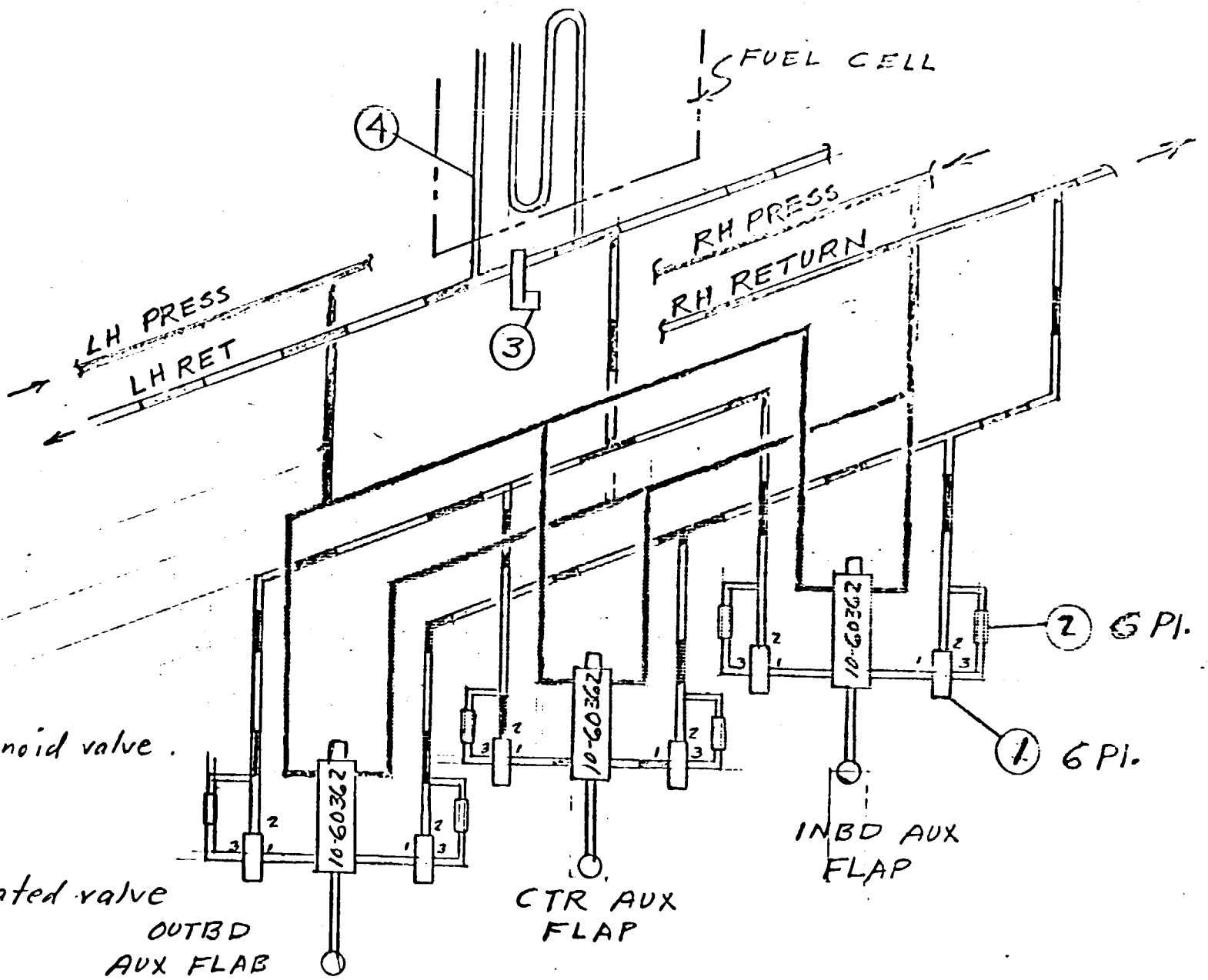
A schematic diagram of the hydraulic supply to the auxiliary flap actuators is shown in Figure 36.

5.3.3.1 Flow Demand

From 5.3.2.4 the actuator saturation rate is 23.8°/sec and the loaded rate at test conditions is approximately 17.2°/sec. The total displacement volume of the actuator is 3.52 in^3. per system which results in the following flow rates:

Displacement Flow

No Load	.545 gal/min
Nominal Load	.395 gal/min
Leakage Flow (Electrical Mode)	.33 gal/min
Total Flow (Per Actuator, Per System)	
No Load	.875 gal/min
Nominal Load	.725 gal/min
Total Flow Per System (6 Actuators)	
No Load	5.25 gal/min
Nominal Load	4.35 gal/min



① 3-way Solenoid valve.

② Restrictor

③ Motor operated valve

④ Cooling loop

TYPICAL
(LH SHOWN)

RECOMMENDED SCHEMATIC
DLC HYDRAULIC ACTUATION

FIG. 36

From a previous analysis of the 367-80 hydraulic system the normal steady state requirement for flight control and other services is:

10 gal/min for the L.H. System

5 gal/min for the R.H. System

Adding to the above the requirements of the auxiliary flap actuators results in a total flow requirement using nominal load flow rates for the auxiliary flaps:

14.35 gal/min for the L.H. System

9.35 gal/min for the R.H. System

The pump capacity of L.H. and R.H. Systems is 16.6 gal/min each at idle power (58% N_2), so it is seen that the available capacity is sufficient although marginal in the case of the L.H. system. It is recommended that the hydraulic system operating procedures be amended to include use of the electrical "ground pumps" during test conditions where auxiliary flaps are used. Additionally in the foregoing analysis it is assumed that no operation of the landing gear or main flaps will be required while the auxiliary flaps are operating.

5.3.3.2 Cooling

In the absence of heat rejection data on the existing system, it is assumed that the additional heat rejection due to the system changes must be removed from the hydraulic fluid.

Heat Rejection	L.H. System	R.H. System
Actuator Leakage Flow 1.96 gal/min or 3.43 HP	145 BTU/min	145 BTU/min
Ground Pump (estimated)	317	---
	462 BTU/min	145 BTU/min

This heat will be rejected to the fuel by placing a cooling loop in each of the inboard fuel cells. Based on B-52 data the following heat transfer rates are assumed for plain aluminum tubing 3/4 in O.D. x .049 in. wall thickness with MIL-H-5606 hydraulic fluid at 150°F and JP-4 at 75°F.

Hyd. Flow Rate	BTU/min/ft
5 gal/min	8.5
10 gal/min	9.0
15 gal/min	10.4

Tubing length required is estimated to be:

L.H. System

$$\frac{462}{10.4} = 44.5 \text{ ft.}$$

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R.H. System

$$\frac{145}{9.0} = 16.0 \text{ ft.}$$

The cooling loop is placed in the hydraulic return line. For symmetry and simplicity or operation, equal length loops should be put in both L.H. and R.H. systems and both electrical pumps operated during test conditions.

5.3.4 Alternative designs

It is evident from the data presented that the actuation system as designed may be marginal in meeting the program objectives. Accordingly several alternative designs were considered before settling on the one described. The two principle alternatives and the reasons for discarding them are discussed in this section.

As mentioned previously, the alternative choice in an actuator was the unit developed for the B-52 LAMS program elevator actuator (Boeing Dwg. No. 10-30378). This unit had several advantages including slightly higher output moment capability and several times the saturation rate of the actuator selected as well as several other desirable features. However, vendor price quotations indicated about double the cost per actuator compared to the selected actuator.

The inboard auxiliary flap has the largest hinge moment and is also the most effective in lift increment. Splitting this auxiliary flap into two segments, each with its individual actuator, would provide more hinge moment margin, but the resulting flow demand would be excessive for the L.H. hydraulic system. Installation of a larger capacity pump on the #1 engine and associated revision of the system would be required. It was not felt that the cost of this modification and the additional actuators was justified by the small performance improvement which would result.

LIST OF ACTIVE PAGES

SECTION	PAGE NUMBER	REV SYM	ADDED PAGES								SECTION	PAGE NUMBER	REV SYM	ADDED PAGES							
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	1											48									
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